PREPARING PGW FOR A LOW-CARBON FUTURE

October 2019

Oscar Serpell, Wan-Yi “Amy” Chu,
Benjamin Paren, and Girish Sankar

Kleinman Center
for Energy Policy

SUPPORTED BY
GOLDSMITH
RESEARCH
FUND
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EXECUTIVE SUMMARY

Climate change is forcing cities, countries, and corporations around the world to reassess the vulnerability and liability of their assets and planning procedures. In Philadelphia, the municipally owned gas utility (PGW) is faced with a number of considerable challenges related to regional emissions targets and state or federally imposed carbon constraints.

Natural gas distributed by PGW contributes nearly one-fifth of the city's carbon emissions, and alone is responsible for at least $184 million in externalized global warming costs each year. The transition to a carbon-constrained energy system poses an existential threat to the company, and a significant financial risk for the company's residential, commercial, and industrial customers who are likely to foot most of the cost.

To protect Philadelphia from this vulnerability, and to work toward its ambitious emission goals, the City is considering options for how to decarbonize the energy demand currently met by the PGW network. This report explores two possible strategies for achieving this carbon neutrality.

The first strategy is to maintain the existing PGW network and gas-powered end uses but to replace the natural gas with synthetically produced carbon-neutral methane fuel. This would avoid expensive appliance replacement for PGW customers and would maintain the current use of the pipeline network. It would also, however, require the regional construction of expensive and groundbreaking facilities in order to produce methane using just water, renewable electricity, and captured CO_2.

The second decarbonization strategy is to electrify regional heating demand and meet the increased electricity demand with renewable grid capacity. This strategy would force the retirement of the existing pipeline network and all distributed gas-fired heating appliances including boilers, stoves, and furnaces. It would also require any investments in storage and distribution infrastructure needed to handle the increased load.

Both strategies prove to be extremely expensive endeavors due primarily to the enormous energy demand that PGW currently meets. In this analysis, we explore several meaningful challenges unique to each strategy, in order to distinguish the likely impact on the region and to assess both strategies against a business as usual scenario.

The fuel replacement strategy has a high demand for land, and because of the efficiency gains accrued from proximity, land used for creating the synthetic fuel should be located somewhere within the region. The electrification strategy also demands many square miles of renewable energy generation, but this demand can more easily be met from anywhere within the PJM footprint. The fuel replacement strategy also has approximately double the annual electricity demand of the electrification strategy because of the technological inefficiencies of electrolysis. However, synthetic fuel provides an intrinsic storage solution for seasonal heating, where the electrification strategy does not.

The electrification strategy, though more efficient, would require additional storage in order to meet seasonal demand. Electro-chemical storage capacity is costly and technologically ill-suited for seasonal storage because of self-discharge and capacity loss. Finally, the electrification strategy renders PGW obsolete, at least in its current role as a gas utility. Under the electrification strategy, the City would need to decide whether to transform PGW into a municipal power provider, permanently ceasing operations and transferring all energy services to PECO, or embrace some hybrid combination of the two.

Ultimately, this analysis concludes that the cost implications and unknown parameters of each strategy are extremely significant, especially compared to simply maintaining the gas network and existing natural gas supply. Nevertheless, both strategies provide emissions reductions not offered by a business-as-usual scenario.

Meeting carbon emissions goals (either self-imposed or mandated by other levels of government) requires the City to prioritize decarbonization, and both of these strategies can help achieve that goal. However, a balanced and measured combination of elements from both strategies is likely the most resilient, efficient, and future-proof method of system decarbonization owing to the high capital and energy costs of both strategies.

INTRODUCTION

Last fall, the Philadelphia Office of Sustainability released a report titled "Powering Our Future: A Clean Energy Vision for Philadelphia." In this report, Mayor Jim Kenney pledges to support a city-wide effort to achieve an 80% reduction in carbon emissions by midcentury. Achieving this goal and keeping Philadelphia in line with the global targets outlined in the Paris Climate Agreement will require a multi-faceted approach to addressing regional electricity generation, building efficiency, industrial emissions, and distributed resources. It will also require that the city develops a comprehensive and emissions-focused solution to the natural gas distribution network owned and operated by Philadelphia Gas Works (PGW) (Hughes 2019).

PGW is the largest municipally owned utility in the United States (Ershkowitz 2015). It manages over 6,000 miles of pipelines and serves half a million customers with natural gas for heating and cooking. Annually, PGW delivers 78 billion cubic feet of natural gas, contributing 4.6 million tons of CO_2e to the region's carbon budget (*pgworks.com*).

A 2012 assessment lists natural gas's contribution as 17% of citywide carbon emissions (Philadelphia OOS 2012). Without addressing the carbon emissions facilitated by PGW's network, achieving the city's ambitious 80 by 50 emissions goals would essentially require the rest of the city to go completely carbon neutral.

Furthermore, until PGW addresses its emissions profile, it remains vulnerable to the imposition of state or federal carbon pricing. Whether through Pennsylvania joining the Northeast Regional Greenhouse Gas Initiative (RGGI) cap-and-trade program, or through a federally imposed carbon tax, it is increasingly likely—and appropriate—that PGW will be subject to additional costs dependent on their system-wide emissions over the coming decades.

Passing these costs on to consumers will significantly increase the burden of energy costs on many Philadelphians. Attempting to absorb the costs without rate hikes on customers will likely lead to severe financial distress and possibly an unsafe lack of maintenance on the system.

THE STATE OF PGW

In 2014, the City of Philadelphia very nearly agreed to sell the utility for $1.86 billion (WHYY 2014). This deal, which had Mayor Nutter's support, would have relieved the city of considerable PGW debt, and would have bolstered the city's pension funds, to which the proceeds would have been devoted. However, the deal was eventually stalled by city council and, four years on, PGW remains a municipal asset.

PGW borrows money by issuing periodic capital raises via revenue bonds. The payment of interest and future principal on these bonds is guaranteed via a portion of PGW's natural gas related revenue stream. These bonds generally carry an interest rate of 2–5% and have been issued across 15 series; the last of which was in August 2017 and raised the company $273.1 million (KPMG 2018). PGW's revenue bonds are used as a source of reserve capital via a sinking reserve fund. This fund goes toward the capital asset improvement and maintenance program and is generally used as a way to pay back and refinance old debt.

PGW has increased its latest reported long-term debt load to over $1,062,763,000 at year-end 2018 vs. $881,620,000 at year-end 2016 (KPMG, 2018). To ensure business continuity, future raises should be used to refinance or pay back debt rather than augment the level of total indebtedness. The amount of leverage that the company maintains is higher than what a private company could get without the backing of the municipality, and this municipal status carries with it a material risk.

When considering what PGW's assets could be worth in the event of financial distress, it is important to note that the company's pipelines are part of an integrated network and are not easily siloed or separated. Pipeline connections span distinct neighborhoods, making it difficult to separate out disparate parts of the pipeline assets.[1] This inflexibility distinguishes PGW from some other past municipal asset bankruptcies.

Before declaring bankruptcy in 2006, the power generation company Calpine had nearly 29,000 MW of electricity generating capacity operating or under construction in more than half of the lower 48 states and three Canadian provinces. The company was able to slash its overall debt during its stay in Chapter 11 by about a third ($7.2 billion) (NGI 2008). Similar to PGW, Calpine had a large amount of leverage but emerged from bankruptcy by selling assets.

Similarly, when the El Paso electric utility experienced bankruptcy, it was able to sell off distinct assets to make its creditors whole and operate after bankruptcy as a leaner organization. PGW would likely not be able to do this without selling off the pipeline network as a whole and thus rendering continued operation impossible. Therefore, PGW is unlikely to survive a period of severe financial distress such as the one carbon pricing could precipitate.

Fortunately for PGW, the company looks to be in a relatively safe operating position today, with over $200M of cash on the balance sheet, $103M in the sinking fund, and another $50M in the capital improvement fund. However, this could quickly change in a carbon constrained future, and the utility needs to be prepared for this.

The implications of a carbon price imposed on PGW are alarming. If a realistic $40/ton CO_2 tax was imposed on the utility, the tax liability to PGW would be close to $184 million per year.[2] Unless these costs are passed on to consumers through a PUC approved rate hike, this would deplete the entire sinking reserve fund in less than a year. PGW's latest excess of revenues over expenses (operating income) in 2018 was $62M—not an amount that could help sustain this ideated carbon tax in the long-run. If the full costs imposed by a $40/ton carbon tax were passed on to PGW's customer base, the average residential bill would increase from approximately $921 per year to approximately $1,100 per year, a roughly 20% increase in cost. For commercial and industrial customers who benefit from lower gas prices, the price increase would be even more pronounced.

1 Insight provided to authors during a phone interview with an executive from Liberty Energy Trust

2 40 countries have already implemented national carbon taxes, and six have tax rates already above $40/ton ranging from $50 to $130.

TWO METHODS OF DECARBONIZATION

For the reasons stated above, it is in the region's best interest if steps are taken to rapidly decarbonize the energy demand currently supplied via the PGW pipeline network. To achieve system-wide decarbonization, there are two general strategies that could be adopted. One option would be to decarbonize the end uses of PGW's natural gas by replacing gas-fired heaters, boilers, and stoves with corresponding electrical appliances, powered by renewable electricity.

The other option for system-wide decarbonization would require replacing the natural gas currently being used in the system with a carbon-neutral alternative fuel that is compatible with the existing distribution infrastructure and end-use appliances. This second option has the benefit of not requiring any additional investment in the pipeline network or behind-the-meter, but it does carry its own considerable engineering challenges. In order to produce carbon-neutral methane fuel that is also compatible with the existing network, one would need to synthesize the methane from a renewable source of hydrogen gas and CO_2 in a process known as methanation.

The prevailing theory these days is that electrifying as many end-uses as possible is the quickest way to achieve deep decarbonization. While the production of zero-carbon synthetic methane at first appears prohibitively expensive, the choice becomes far more opaque once the full implications of city-wide electric heating are considered.

On the one hand, electrolysis of water into H_2 and O_2 is extremely energy demanding and the land use of atmospheric CO_2 capture is considerable. On the other hand, the seasonal variation in grid electricity demand that electrified heating would create has no obvious storage solution. Electrochemical batteries are generally seen as the most promising method of large-scale storage but are poorly suited for long-term seasonal storage. In this report, we take a deep dive into the full costs and benefits of these two strategies in order to better inform decision makers and stakeholders about the available options to address this important issue.

THE CHALLENGES OF METHANATION

The major component of fossil-derived natural gas is methane, a naturally occurring hydrocarbon (CH_4). The high calorific value of methane has made it a popular choice for heat generation around the world and, in recent years, its emissions advantage over fuel oil has allowed it to largely evade the attention of decarbonization efforts. In the context of a fully decarbonized electrical grid, production of synthetic methane can be thought of as a delivery system that easily transports and stores energy using existing infrastructure.

Carbon neutral methanation involves capturing electrical energy in the form of synthetic methane, and therefore the efficiency of transformation is key to economically viable large-scale production. Specifically, synthetic methane with net-zero production of carbon dioxide, would require three major components: capture of carbon dioxide, electrolysis of water to generate hydrogen, and processes for the chemical reaction of these two components to afford methane. To be exact, in order to meet PGW's existing demand with 100% synthetically produced methane, 4.34 megatons of carbon dioxide and 790 thousand tons of hydrogen will need to be captured or generated every year. Each of these areas entail challenges that are addressed below.

The most daunting technological challenge to economic carbon dioxide capture is its land use. Three sources are typically considered for sequestration of carbon dioxide: flue gas of traditional power plants, biological sources, and the atmosphere. Since we are discussing a completely decarbonized electricity grid using renewable resources, traditional power plants based on fossil fuels will eventually be phased out and are not considered in this analysis as a source of recycled CO_2.

Bioenergy with carbon capture and storage (BECCS) uses carbon dioxide generated from crop waste or biogas from landfills. The gases are produced by microorganisms as they decompose the waste and are then captured and converted into usable carbon-neutral fuels. The land use of BECCS is substantial, and even the most optimistic estimates will still demand 1,200 km^2 of land to generate enough carbon dioxide for PGW (Smith et al. 2016).

On the other hand, direct air capture (DAC) of carbon dioxide from the atmosphere is a relatively new technology with reduced land requirements. A few pilot-scale DAC plants already exist and are producing small quantities of recycled carbon dioxide by pulling air through a capture medium and taking CO_2 directly out of the atmosphere.

Carbon Engineering, a DAC company based in British Columbia, has been operating a unit since 2015 that captures 220 tons of carbon dioxide a year (*Carbonengineering.com* & Keith et al. 2018). To supply the carbon dioxide needs of PGW, about 20,000 of these units, and 100 km^2 of land (~0.005 km^2 per unit), will be needed; approximately a quarter the size of the city itself (367 km^2). This estimation is based on Carbon Engineering's pilot plant; however, the eventual industrial-sized plant may require far less land given the economy of scale, technological advancement, and system efficiencies. Estimations published in peer-reviewed journals are around 12 km^2 for a DAC plant large enough to support PGW's synthetic methane needs (Smith et al. 2016). The reality will most likely be somewhere in between.

Another challenge associated with producing synthetic methane is the demand for clean water. This demand comes from the hydrogen production step, which uses water as a raw material in the electrolysis process. A 2015 report from Argonne National Lab provides a low estimate of 2.9 gallons of water per kilogram of hydrogen produced from water electrolysis, or 2.3 billion gallons a year needed to generate methane for PGW.

To put that in context, 84 billion gallons of drinking water is supplied to Philadelphia every year (Philadelphia Water Department, 2018). Although the electrolysis step of synthetic methane production would have a moderate impact of regional water demand (~3% growth), it is unlikely to significantly strain the existing water distribution system or require any major investment in treatment capacity.

Once the required carbon dioxide and hydrogen is obtained, conversion to synthetic methane can be achieved through biological or thermochemical means. The biological route, also called biomethanation, uses microorganisms to synthesize methane. This process has a high tolerance for impurities in the gas feed and allows biomethanation reactors to directly utilize biogas as feed with minimum gas cleanup.

An innovative project spearheaded by the National Renewable Research Laboratory in collaboration with SoCalGas uses biomethanation to upgrade biogas into grid quality methane (NREL). However, this process uses biogas as the carbon dioxide source. The intense land demand of biogas will likely make this process infeasible on the scale needed for PGW. Even if DAC is to be implemented instead of using biogas, biomethanation is characterized by slow rates of methane production and the need for large volume reactors.

These properties of biomethanation demand incredibly large facilities to accommodate the reactor volumes required to produce enough synthetic methane for entire urban regions. Biomethanation technologies have so far been limited to applications in converting relatively small quantities of excess renewable electricity and is likely not suited for use on the scale required by PGW.

The alternative thermochemical route to produce synthetic methane is known as the Sabatier reaction. The Sabatier reaction can be conducted under high temperatures, allowing for increased rates of reaction, and making the process suitable for large-scale replacement of fossil-derived natural gas. A plant designed for the European project Store&GO (Store&GO) that encompasses hydrogen production, DAC, and methane synthesis using the Sabatier reaction can be used as a basis for calculating the overall energy demand of a hypothetical industrial facility that could meet PGW's demand (Figure 1).

To generate 78 billion cubic feet of synthetic methane (bottom black arrow), 43,000 GWh/year of renewable electricity is needed (green arrows). Notably, this calculation is a simple scale-up of the reported Store&GO design and does not account for any economies of scale. The most electricity intensive step in this design is the electrolysis of water using an alkaline electrolyzer, which will require 41,550 GWh.

The rest of the energy is used for DAC, which is predominantly powered by recycled heat from the electrolysis. The Sabatier reaction is entirely powered by recycled heat from the heat-releasing methanation reaction itself. This design has yet to be realized and the actual energetic cost may vary. However, the currently operational Audi E-gas plant in Germany offers a glimpse into the reality of this strategy. Audi has reported similar electricity demands of 0.520 kWh per cubic foot of synthetic methane produced, similar to the 0.55 kWh per cubic foot estimated in figure 1 (Otten 2014).

In addition to the electrical demands of generating synthetic methane, construction of the new processing plants will not come cheap. Outotec Gmbh reported capital investment costs of $0.15/W to $0.40/W for the methanation process alone (Gotz et al. 2016). The price is dependent on the capacity of the methanation process. If PGW invests in large methanation plants with 110 MW capacity, the capital cost would total a modest $420 million. Capital investments for electrolysis and DAC are far more expensive. The current consensus for the capital costs of electrolyzers lies around $0.35/W, which would require an investment of $1 billion for equipment to generate hydrogen (DOE).

FIGURE 1: CO_2 CAPTURE, ELECTROLYSIS, AND METHANATION FLOW DIAGRAM

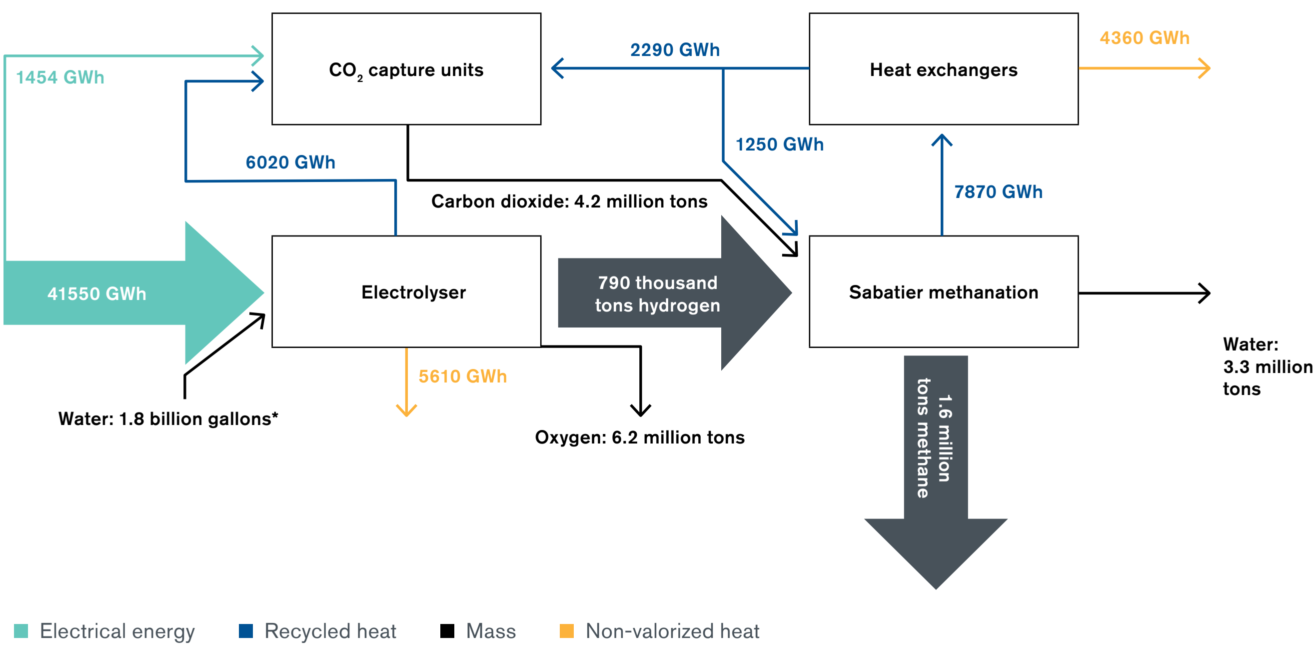

Figure adapted from the design of the Store&Go facility in Morosanu et al., 2018. The energy demands have been scaled up so that the output energy of the system—in the form of methane gas—is equal to PGW's network demand. The methane gas cleanup and liquification steps in the original process have been omitted in this adapted design. The diagram is color coded to show energy inputs, used and unused heat, and movement of matter.

*Does not include process water

TABLE 1: SUMMARY COSTS AND RESOURCE DEMANDS OF THE METHANATION STRATEGY

Type of Resource	Demand
Capital Cost	$4.92 billion
Customer Annual Bill Cost	$2630–$3139
Equivalent Carbon Price	$381/ton CO_2e
Land Use Demand*	12–100 km^2
Annual Electricity Demand	43,000 GWh

*Does not include the land required for renewable electricity generation

The DAC configuration reported by Carbon Engineering may cost PGW up to $3.5 billion dollars.[3] Adding the cost of renewable electricity and capital investments (assuming a lifetime of 40 years for the production plant), the cost of synthesizing natural gas lies in the range of $0.035 to $0.041 per cubic foot, depending on the source of renewable electricity (assuming electricity costs of $0.06/kWh to $0.072/kWh).

An average household that consumes 76 thousand cubic feet of natural gas per year will see their annual gas bill rise to $2630 to $3139, approximately a 300% increase on the average residential gas bill today. For a carbon price to increase customer's bills by this much, PGW would have to pay $381/ton of CO_2e.

THE CHALLENGES OF ELECTRIFICATION

The alternative to creating carbon-neutral fuel to be used in PGW's existing network is to instead electrify the end uses of natural gas in all of Philadelphia and retire the existing pipeline network. To estimate the energy demand and capital costs of this decarbonization strategy, the process of electrification must be understood.

A standard electric heat pump is rising in popularity as an option for all-electric heating and cooling, as well as water heating. A heat pump uses electricity to move heat, as opposed to generating heat, so the efficiency is calculated as the amount of heat moved divided by the amount of electricity required to move this heat. This is different than a traditional heater, whose efficiency is the amount of heat generated divided by the amount of electricity or gas used to generate that heat. Therefore, under certain weather conditions, this technology can operate at efficiencies exceeding 100%, because it requires less energy to move air than the energy that comes from the heat of the air itself (True North Energy Services).

The cost of a heat pump can vary based on size and location, but the average price we will use for this analysis is $10,550 for a heat pump installation for a standard residence in Philadelphia, with a lifetime of approximately 15 years (Billimoria 2018). In comparison, the average cost to replace a gas heater is approximately $4,700. Based on roughly 472,000 residential PGW customers (see appendix 2), this means a cost between $2.5 and $5 billion to install heat pumps as a replacement for residential natural gas heaters in Philadelphia, depending on whether or not residents have the opportunity to wait until their existing system needs replacing (DVRPC 2010).

This only accounts for the space and water heating requirements and ignores the use of the heat pump as an air conditioner. Cooling is not a contributor to PGW's natural gas demand and is therefore not considered in this analysis. Cooking also contributes a small amount to residential gas, so gas stoves would also need to be replaced with their electric counterparts. The average cost

3 Based on total project cost estimated for the Nth plant that has a capture capacity of 0.98 megatons of carbon dioxide per year.

of an electric stove is $680; cheaper than gas stoves, which cost an average of $1,010 (Fixr & ATD).

However, if a resident was required to replace their gas stove before it is needed, the capital cost of an electric stove could be significant: as much as $320 million city-wide. Instead, if the electric stoves were phased in over the lifetime of a stove, electrification could occur at no additional cost, and would actually save consumers as much as $160 million city-wide. Although older customers are persistently opposed to electric stoves, there is some indication that younger generations are warming to the idea of induction cooking (Severson 2010).

Beyond the capital costs of replacing gas-powered equipment, a key factor in the affordability of this strategy is the cost of electricity required to power these new heat pumps and stoves. Although electric stoves are not 100% efficient, cooking is only a small share of the gas used by residential customers, and since heat pumps may at times exceed 100% efficiency and are replacing a larger share of the gas demand, this analysis assumes an average efficiency of 100% for new electrical appliances. This means that the total electricity demand of replaced residential natural gas demand would equal 10,904GWh/year (DVRPC 2010).

PGW has 472,000 residential customers, each using an average of 760 CCF (hundreds of cubic feet) per year. In 2016, the cost of gas from PGW was approximately $1.21 per CCF (*PGW.com*). If these costs are unchanged, the natural gas used by the average residence costs $921 per year. However, those costs change significantly when demand is replaced by 10,904GWh of required renewable electricity. Based on 2017 solar costs throughout the United States, the price ranges from $0.06–$0.16/kWh depending on whether it is utility scale (cheapest), commercial, or residential generation (DOE).

Wind energy costs in Pennsylvania and the northeast U.S. ranged from $0.072 to $0.09/kWh in 2018 (NREL).[4] Because we are assessing the costs of grid-connected electricity demand, we assume utility scale generation and therefore use the lower range of these per-kWh costs. Furthermore, for the simplification of this analysis, we are assuming that cost reductions from technological advances may offset the elimination of tax credits or subsidies in the future.

In an ideal scenario, where there is sufficient generation and storage for constant use of wind or solar, then the annual cost to each residence would be between $1,386 (all solar) and $1,663 (all wind) to immediately replace the natural gas that is currently being used. This is an increase of $465 to $742/year for each household compared to the current costs of natural gas.

Even if the cost of renewable electricity decreases as time goes by, this could still be unattainable for many low-income households without significant energy subsidies. Furthermore, this analysis ignores the costs of energy storage which will be critical to combat the intermittency of wind and solar generation. Those costs will significantly increase the cost to the consumer of renewable generation.

A follow up analysis will be published which focuses more specifically on the actual costs of seasonal, grid-level energy storage. Unlike the methanation strategy, however, the electrification could avoid approximately half of its capital costs by phasing in the transition to electric heating over the lifetime of a gas heater. These potential savings would likely be somewhat reduced by customers' stated preference for gas stoves.

In addition to the residential customers, there are industrial and commercial customers who use 346 million CCF of gas per year (DVRPC 2010). Some of this demand is for high-heat and specialized processes that would be costly and difficult to electrify. One could conclude that only that difficult-to-electrify demand should be maintained and the rest should be electrified, however this transition would present enormous challenges for PGW. In order to maintain difficult-to-electrify industrial demand and critical backup power on an integrated network that is not easily siloed, PGW would have to either maintain the entire network just to meet critical demand, or all gas demand in the city would have to be electrified. The costs of

4 Several caveats are needed here. Firstly, this analysis does not take tax credits or grants into consideration as the continued existence of these policies is difficult to predict. Secondly, we do not assume any technological cost reduction. These reductions will depend on the timeframe of the strategy implementation. Finally, this analysis assumes that wind and solar power are provided to customers at cost since service and transportation fees will already be included in electricity bills. Because the LCOE from new wind and solar is lower than the lowest existing electricity cost to consumers, it was assumed that all customers (residential, commercial, and Industrial) receive the same at cost electricity.

maintaining the full network are significant and, based on PGW 2018 financial statement, likely contribute at least $87 million to the company's annual operating expenses (KPMG). Therefore, the most viable option for complete decarbonization using electrification is to electrify all gas demand including high-heat and specialized processes.

Electrifying all commercial, and industrial demand would add an additional 11,944GWh of electricity demand annually. It is beyond the scope of this analysis to perform a comprehensive breakdown of all of the varied capital costs associated with electrifying these industrial and commercial customers. As a simple proxy, it can be assumed that the capital costs and energy costs per/kWh is consistent across residential, commercial, and industrial customers.

If we level the cost of heat pumps and electric stoves for residential customers by their 15-year lifetimes, this is roughly $0.032/kWh. To meet the 11,944GWh commercial and industrial demand, this corresponds to $5.7 billion in total capital costs or $382 million in annual capital costs for the commercial and industrial sectors city-wide. Furthermore, using the same assumptions about renewable generation costs as with residential customers, the city-wide cost of energy for electrification of the commercial and industrial sectors is $716 to $860 million annually.

It is important to note that the largest asset on PGW's balance sheet is the pipeline network itself, valued at about $1.4 billion. In the event of financial distress, this is the company's main collateral, after a sinking reserve fund which as of year-end 2018 contained only $103 million. If all of PGW's natural gas demand is electrified, the utility's primary asset will become largely valueless unless an alternative use for the 6000-mile pipe system can be found. In making the pipelines obsolete, the electrification strategy also makes PGW, in its current role as a municipal gas provider, obsolete.

Under this strategy, PGW would either have to permanently suspend operations, or transform its business to provide Philadelphia customers with another municipal service. In all likelihood, PECO would become the primary regional provider of heating services within city limits. The transfer of this service from the municipally owned pipelines to a privately-owned electricity distribution grid should be taken into consideration by decision-makers, especially when considering the role of PGW in an electrified future.

To summarize our assessment of the requirements for electrification of the heating demand currently met by PGW, the total annual electricity demand would be 22,848GWh, with 10,904GWh of this for residential customers, and 11,944GWh for industrial and commercial customers. The total cost of the electrification strategy to each residential customer would be $1,386 to $1,663 annually, an increase of $465 to $742/year compared to natural gas heaters. For a carbon price to increase customers' bills by this much, PGW would have to pay $104/ton of CO_2e.

TABLE 2: SUMMARY COSTS AND RESOURCE DEMANDS OF THE ELECTRIFICATION STRATEGY

Type of resource	Demand
Capital Cost	< $10.7 billion depending on phase in
Customer Annual Bill Cost	$1386–$1663
Equivalent Carbon Price	$104/ton CO_2e
Land Use Demand*	NA
Annual Electricity Demand	22,848 GWh

*Does not include the land required for renewable electricity generation

STORAGE AND LOAD VARIABILITY CHALLENGES

In order for electrification to be completely dependent on wind, solar, or any form of intermittently available energy, it is critical to have energy storage to balance the variability of these technologies. The maximum generation output of wind and solar vary depending on the time of day, as well as the time of year. Solar capacity is almost entirely non-productive at night and is somewhat less productive in winter months when cloud cover and daylight hours limit solar irradiance.

Wind energy, on the other hand, is somewhat more consistent over the course of a day, and often has a slightly higher output in winter months; however still experiences significant daily, weekly, and monthly variability. Furthermore, the variability of electricity demand does not often correspond with the capacity being generated by renewable energy at any given time. While batteries are already being used by many consumers to combat this daily intermittency, the existing battery technology is not yet well adapted to monthly or seasonal long-term storage and remains prohibitively expensive to implement at the distributional scale even for hourly or daily storage.

Among today's widely available technologies, Lithium-ion batteries are the best suited for large-scale electro-chemical storage. These batteries have dropped considerably in price, but also have several inherent limitations to their effective implementation at the grid level. For one, they remain extremely expensive. The Tesla Powerwall, a highly efficient battery designed for at-home load balancing costs $6,700 and has a 13.5 kWh usable capacity (Tesla).

Using this technology, it would cost more than $38 billion to install enough storage capacity to meet the existing electricity demand of Philadelphia residential properties for one week (DVRPC 2010). Secondly, lithium-ion batteries are subject to self-discharge if they are left with a charge for a long period of time. This is due to the electro–chemical reaction taking place at very low levels even while the battery is not part of a circuit.

Lithium-ion batteries, which today are mostly used in phones and electric vehicles, lose up to 5% of their initial charge in the first 24 hours even if not being used, and then they continue to lose at least 2% of their initial charge per month (Battery University). This means that a brand-new lithium ion battery charged up in June, would only have approximately 80% of its initial charge if used the following December.

This self-discharge gets progressively worse over the lifetime of the battery and is significantly worsened anytime the battery is fully drained or is left uncharged for a period of time. Therefore, after a couple winters in which the load balancing batteries are left uncharged, the self-discharge rate could completely drain the battery in less than six months, rendering it useless for the kind of long-term seasonal storage a renewable grid will require.

While many promising new battery technologies are in development, it is unclear if and when electrochemical storage will be capable of providing sufficient seasonal load balancing for a grid dependent on variable energy sources. If electrochemical storage remains out of reach because of cost or self-discharge constraints, alternative storage technology—with their own limitations—may have to be relied upon. Several of these technologies such as pumped hydro, compressed air, and thermal storage have the advantage of being better suited to monthly or seasonal storage but are otherwise limited by their extremely low energy density and geographical constraints.

Using renewable electricity to electrolyze water and create synthetic natural gas as a means of seasonal energy storage may, ultimately, be the best option for accommodating variable grid demand, despite its inefficiency. These are questions that will be tested in a future policy digest, where we examine the current state of energy storage and the feasibility of its implementation in an all-electric Philadelphia.

COMPARING STRATEGIES

The heating demand that is currently met by natural gas in the City of Philadelphia embodies an enormous amount of energy, and decarbonizing PGW is going to be an expensive and challenging undertaking regardless of the strategy that is used. However, building a zero-carbon heat utility should, nonetheless, be a top priority for the City of Philadelphia both because of the contribution it would make in achieving carbon emissions goals and because of the financial risk a municipally-owned gas utility poses in the event of an otherwise appropriately heavy state or federal carbon price.

From the above analysis, one can see that the electrification and methanation strategies each have some key advantages over one-another. Both are extremely costly and energy intensive, but this is inherent in any plan to replace natural gas in the generation of space and process heat. Natural gas is a cheap and energy dense resource with unaccounted climate externalities. As discussed in the sections above, the on-paper costs of the electrification strategy do not include a number of unknowns with potentially significant implications for the City and PGW customers, and also uses a proxy analysis to determine commercial and industrial costs.

Perhaps the largest unknown under this strategy is the future role of PGW. Without the municipally owned pipelines providing a service to the city, it is unclear what, if any, role PGW could continue to play in the future. It is also unclear what the long-term economic and public safety impacts of an abandoned pipeline system would be. In addition, the cost of storage required to balance seasonal variability could considerably increase the electricity cost that consumers would have to pay for their heating. Lastly, the capital costs of the electrification strategy are extremely dependent on the timeframe over which the strategy is implemented. The more rapidly decarbonization is achieved, the more expensive the strategy will be. The methanation strategy, on the other hand is subject to far fewer potential and unaccounted for costs.

Both strategies face one common challenge for which no obvious solution has emerged: the land use and capital costs of renewable electricity generation. In order for each of the strategies discussed in this analysis to be carbon-neutral, the electricity used to power appliances or the methanation facility needs to come from zero-carbon renewable sources: namely solar and wind.

Because both of these strategies represent new grid demand for the region, the required GWh for each will need to be generated by newly constructed renewable capacity. When considering thousands of GWh of new electricity demand, as we are in this report, the cost and land use of this new renewable capacity would put considerable strain on the region. While the costs of implementing these technologies are already incorporated into the consumer cost through the levelized cost of energy, the need for the capital investment up front will be a major challenge, in addition to the obstacles posed by land use requirements.

FINDING A FUTURE-PROOF MIDDLE GROUND

Thus far, two strategies for utility decarbonization have been discussed as separate and alternative pathways for PGW and the City. This analysis found that cost, design, and technology challenges associated with both the electrification strategy and the synthetic methane strategy were significant. Alone, neither of the strategies discussed in this report offers a cost-effective alternative to the business-as-usual scenario, even with the imposition of a $40/ton carbon price.[5]

The electrification and methanation strategies would require carbon prices 2.5x and 10x as large, respectively, before the strategies could be achieved entirely through market forces. Although $40/ton of CO_2e is a relatively conservative estimation of a possible future carbon price, it is fairly unlikely that a carbon price exceeding $100/ton will fall on PGW in the near future.

If cost minimization were the only goal for the city, PGW should likely continue to operate in its current state, at least for the time-being. However, as already stated, Philadelphia has ambitious carbon emission goals, the success of which will depend on decarbonization being made a public priority despite additional costs. It is therefore appropriate and necessary to consider that a hybrid strategy, made up of elements from both strategies, may be the most efficient and practical path toward decarbonization.

By partially electrifying existing gas demand and meeting the remaining gas demand with zero-carbon sources, the City would be able to take advantage of a number of synergies between the two strategies that ought to lessen many of the challenges and costs discussed earlier in this analysis. For instance, even the partial electrification of winter heating will likely create a steep variation in electricity demand between seasons. One solution to this variation is to build enough renewable capacity to meet annual demand and use storage technologies to defer the use of that electricity to high demand seasons.

Unfortunately, as has already been briefly discussed, electrochemical batteries are technologically inappropriate for seasonal storage and are prohibitively expensive. If, however, PGW used synthetic methane to meet its remaining gas demand, excess electricity supply in the spring and fall could be stored as hydrogen or synthetic methane and used later to meet wintertime heating demand. If the fuel was stored as LNG, a year's supply would require about 970 million gallons of cooled storage space and would cost about $2.9 billion in additional capital investment (Baker 2013). This would not only reduce the cost of hydrogen production (assuming competitive pricing of electricity) but it would also help to offset the load variability introduced by electrified heating.

Another example of a synergy that would be made possible by a hybrid strategy for decarbonization involves behind-the-meter investments. As some households and commercial customers switch their natural gas-powered appliances to electric appliances, other customers could be incentivized to install micro-CHP (combined heat and power) systems in their homes. This technology uses natural gas to heat air and water in the home, but also uses the excess heat to generate electricity. By implementing CHP technology in conjunction with electrification, the wintertime increases in electricity demand from the homes who electrified will be somewhat offset by the decreased electricity demand of homes that are still connected to the PGW network and who have CHP systems.

Similarly, the lost demand for natural gas from the electrified homes would be to some extent balanced by the increased natural gas use of the CHP systems. Overall, regional energy efficiency would improve, but neither service provider would need to absorb as much seasonal variation in demand. Furthermore, this hybrid strategy for behind the meter investment could help reduce overall costs by phasing in new appliances as old appliances age out of the system. This would be possible because under this arrangement, PGW would be able to maintain service distribution consistently throughout the whole pipeline network as individual homes and buildings adapt.

5 It must be noted that this is probably a measure of how little of the total social cost of carbon is accounted for in a $40/ton tax rate.

In addition to these elegant synergies between the electrification and fuel replacement decarbonization strategies, there are also a handful of highly pragmatic reasons for choosing a middle-of-the-road approach to decarbonization. Firstly, a measured approach to building electrification will reduce the risk of PGW experiencing a rapid loss of demand. If too many customers switch to electric appliances without PGW having time to coordinate network solutions, it could lead to severe financial distress and an unsustainable financial burden on customers who were unable or unwilling to switch to electric heating, especially with the introduction of a punitive carbon price.

The electrification strategy analysis makes certain assumptions about the electrification potential of industrial natural gas demand in the city. However, details about the cost and feasibility of this transition are largely unknown and may be much more costly or impractical than was assumed for the purposes of this report. In this case, a distributed electrification strategy may only be capable of electrifying a portion of the city's total natural gas demand. This would present the region with a number of challenges, high among them being the ability to silo PGW's pipeline network to continue supplying industry while systematically closing off the network to electrified residential and commercial customers. In this scenario, assuming a sustainable delivery solution is found, the remaining natural gas demand could be met by synthetic methane production.

Secondly, reducing gas demand through electrification would have a direct impact on the feasibility of meeting remaining gas demand with synthetic methane. As demonstrated in the earlier calculations, the land, water, and electricity demands of synthetic methane production are considerable. The land requirements alone may run up against regional limits, making the production of enough synthetic methane to meet all of PGW existing demand extremely challenging. If PGW's gas demand can be reduced such that synthetic methane production can be comfortably accommodated by regional resources limitations, this will remove the need for any long-distance transportation of hydrogen, carbon dioxide, or methane gas from the point of production to the point of injection into the PGW pipeline network. Such transportation would sacrifice much of the thermal recycling potential of having all industrial processes taking place at a central or district facility.

Finally, owing to the considerable capital costs of carbon neutral methanation—which contribute to the high cost to consumers of that strategy, it is worth considering the possibility of repurposing some of the region's fossil fuel assets—such as those owned by the now bankrupt Philadelphia Energy Solutions (PES)—to be used for either the carbon capture, electrolysis, methanation, or storage processes needed for synthetic methane production.

The challenges and considerations highlighted by the above analysis serve to illustrate the immense undertaking of decarbonizing a natural gas utility. Although it may at first seem logical to assume that the best and easiest way to decarbonize demand is to shift it to the electricity grid, there are alternative pathways that should be considered.

This is especially necessary when the energy demand under consideration will contribute significantly to the seasonal or annual variation in grid electricity demand. By using a combination of fuel replacement and electrification strategies, PGW can become a carbon-neutral utility in a robust and future-proof way, positioning Philadelphia as a climate leader using advanced technologies, and can prepare its customer base for success in a world of carbon pricing and regulation.

APPENDIX

CALCULATIONS FOR THE ELECTRIFICATION AND METHANIZATION STRATEGY

TABLE A1: DATA USED TO CALCULATE COSTS AND REQUIREMENTS OF ELECTRIFICATION

Solar Generation	0.06–0.16 $/kWh [*energy.gov*]
Wind Generation	0.072–0.09 $/kWh [NREL]
#PGW residential Customers	472,000 [PGW]
PGW Residential Gas Use (2010)	358 million CCF/year [DVRPC]
PGW Commercial Gas Use (2010)	116 million CCF/year [DVRPC]
Residential Energy Equivalent	10,904 GWh/year
Commercial Energy Equivalent	4,936 GWh/year
Average Fixed Cost of a Heat Pump	$10,550–15 year lifetime ($703/year) [RMI]
Average Fixed Cost of an Electric Stove	$680–15 year lifetime ($45/year) [Fixr]
Gas Cost from 2016	$1.21/CCF [PGW]
CCF/person/year	760

*Does not include the land required for renewable electricity generation

LAND USE CALCULATIONS

Smith et. al. (Nature Climate Change, 2016) estimates land intensities of 0.1–0.4 ha t^{-1} Ceq yr^{-1} (Ceq is carbon equivalent and is calculated as 27% of the weight of carbon dioxide) for capture of carbon dioxide using purpose-grown energy crops. That equates to 0.027–0.11 ha t^{-1} CO_2 yr^{-1}, or 0.00027–0.0011 km^2 t^{-1} CO_2 yr^{-1}. At the lowest range, 1200 km^2 will be needed for the 4.34 megatons of CO_2 required for capture.

Similarly, Smith et. al. estimates <0.001 ha t^{-1} C_{eq} yr^{-1} for DAC, equating to < 0.00027 ha t^{-1} CO_2 yr^{-1}. For 4.34 megatons of CO_2 to be captured, 1183 ha, or 12 km^2, is needed.

METHANATION COSTS TO CONSUMERS

$4.92 billion / 40 years = $123 million each year

$123 million / 78 billion cubic feet = $0.0016 per cubic foot additional cost on top of electricity costs.

Energy costs
43,000 GWh * $0.06 = $2.58 billion per year

43,000 GWh * $0.072 = $3.1 billion per year

$2.58 billion/ 78 billion = $0.033 per cubic foot

$3.1 billion/ 78 billion = 0.0397 per cubic foot

Add the capital costs
0.0346–0.0413 per cubic foot

Per household cubic feet = 76,000

Annual cost per consumer = $2629.6–$3138.8

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ABOUT THE AUTHORS

Oscar Serpell is a research associate at the Kleinman Center for Energy Policy.

Wan-Yi "Amy" Chu is a temporary lecturer and researcher at Cal State University in San Francisco and former postdoctoral researcher for the Goldberg Group at the University of Pennsylvania.

Benjamin Paren is a Ph.D. student in the department of Materials Science and Engineering at the University of Pennsylvania.

Girish Sankar is a MBA/MA candidate in the Wharton School at the University of Pennsylvania.

This project is being conducted under the supervision of Dr. Mark Alan Hughes, as part of the Kleinman Center's multi-year research on the future of energy in Philadelphia and its metropolitan area.

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Kleinman Center for Energy Policy

University of Pennsylvania
Stuart Weitzman School of Design
Fisher Fine Arts Building, Suite 401
220 S. 34th St.
Philadelphia, PA 19104

P 215.898.8502
F 215.573.1650

kleinmanenergy@upenn.edu