ENVIRONMENTAL RESEARCH
LETTERS

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To cite this article: Eric Daniel Fournier *et al* 2020 *Environ. Res. Lett.* **15** 124008

Environmental Research Letters

OPEN ACCESS

RECEIVED
11 April 2020

REVISED
13 June 2020

ACCEPTED FOR PUBLICATION
1 July 2020

PUBLISHED
18 November 2020

LETTER

Implications of the timing of residential natural gas use for appliance electrification efforts

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Keywords: decarbonization, residential building energy, hourly data, electricity, natural gas, electrification, California

Supplementary material for this article is available online

Abstract

Current strategies for deep decarbonization of the residential building sector invoke the following three pillars of action: (1) radically improve the efficiency of end-use electricity consumption, (2) shift to 100% renewable generation of electrical grid power, and (3) move aggressively to electrify all remaining fossil fuel end-uses. Due to the previous unavailability of high temporal resolution natural gas consumption data, the pursuit of this policy agenda has largely occurred in the absence of a thorough understanding of hourly variations in the intensity of household natural gas use. These variations can have important downstream impacts on the electricity system once electrification has been achieved. This study presents a series of analyses which are based upon a novel dataset of hourly interval natural consumption data obtained for (N = 17,072) households located within a low-income portion of Southern California Gas Company's service territory. Results indicate that diurnal patterns of hourly natural gas use largely coincide with the timing of daily peak electricity loads. These findings suggest that the aggressive electrification of residential end-use appliances has the potential to exacerbate daily peak electricity demand, increase total household expenditures on energy, and, in the absence of a fully decarbonized electrical grid, likely result in only limited greenhouse gas emissions abatement benefits.

1. Introduction

1.1. Deep decarbonization pathways

Among global OECD countries, energy consumed within residential buildings can account for between 16–22% of total domestic primary energy use [1]. The greenhouse gas (GHG) emissions associated with this consumption is a major contributor to anthropogenic global climate change. Within the U.S., integrated assessments conducted at both the state and national levels have found electrification to be the cheapest and most efficacious approach to the deep decarbonization of the residential building sector [2–5]. A pair of 2017 studies published by National Renewable Energy Laboratory (NREL) investigating the potential impacts of widespread electrification found that existing barriers within the residential building sector could be overcome with public intervention [6, 7]. These studies also concluded that while the electrification of space and water heating end-uses would increase electricity loads, the rate and extent of this growth could be effectively managed through concomitant energy efficiency measures.

Investigations of California's residential energy sector funded by the California Energy Commission (CEC), the California Public Utility Commission (CPUC), and others have arrived at similar conclusions. A 2015 review of statewide energy models with GHG mitigation scenarios found that electrification of residential buildings was a less costly and uncertain option for meeting the state's GHG abatement goals than the other alternatives considered, including those involving the large scale production of renewable gas [8]. A 2019 CPUC funded study of low-rise residential building electrification also came to a similar conclusion: assuming that government intervention sufficiently decreases the cost of fuel-switching and increases residential energy efficiency, electrification was deemed the most feasible and least costly approach [9].

1.2. California's policy context

California is the world's fifth largest economy and, due to its historically progressive legislature, has become a testbed for energy policy innovation. The state's efforts to decarbonize residential buildings are subsumed under its major climate change mitigation law, Assembly Bill 32 [10]. Passed in 2006, AB 32 gave the California Air Resources Board (CARB) the authority to plan and coordinate efforts to meet initial GHG abatement targets set earlier that year by Executive Order S-3-05 [10]. AB 32 directed CARB to create a Climate Change Scoping Plan, in which:

> *...the maximum technologically feasible and cost-effective reductions in GHG emissions from sources or categories of sources of GHGs were to be identified and pursued* [11].

Public agencies are then responsible for devising and implementing measures to realize these reductions, and ensuring that the entities they regulate comply.

Accordingly, California is moving to expand programs to encourage residential electrification. In 2019 the CPUC decided to allow investor-owned utilities (IOUs) to offer incentives for electric space and water heaters as part of their energy efficiency programs, on which over a billion dollars are spent annually [12]. As of 2020, the CPUC has begun considering whether to introduce additional fuel-switching incentives directed at residential consumers [13]. Decarbonization efforts are also supported by the CEC's funding of related research studies, policy evaluations, and demonstrations of new efficiency and electric heating technologies.

California's push to decarbonize its residential building sector comes during an awkward economic moment however. The explosion in domestic natural gas extraction enabled by hydraulic fracturing has led to precipitous declines in the price of natural gas [14]. Meanwhile the costs of generating and transmitting electricity are expected to rise in the short and medium-term, driven by aging grid infrastructure and the integration of more renewable generating capacity in accordance with the state's Renewable Portfolio Standard (RPS) [15, 16]. These price trends may weaken incentives for consumers to electrify end-uses of natural gas and other fossil fuels, slowing the proliferation of electric heating technologies in existing buildings, and increasing energy costs for those consumers already living in fully electrified structures.

The decision by the CPUC to require IOUs to transition all of their customers to Time-of-Use (TOU) rate structures also potentially complicates decarbonization of the residential building sector. Initiated by CPUC Decision D.15.07-001, IOUs were to begin transitioning residential customers to TOU rates in 2019, but the rollout of these new rate structures has been delayed in some instances to 2020 or 2021 out of concern for their impacts on low-income customers and other implementation issues [17]. TOU rate structures are intended to better match the supply of renewable energy with demand by disincentivizing consumption during peak periods. This, it is hoped, will reduce the need for additional investment in generation and transmission infrastructure. However, the effects of TOU rates on the total expenditures on energy among different customer groups are still uncertain [18, 19].

There have been a number of recently published studies focused on the systemic impacts likely to result from the more widespread electrification of California's residential building sector [20–22]. In all of these however, diurnal patterns of gas use were either estimated or inferred using a combination of national lab reference data, ground-up physics based simulation model results, and household survey responses. This study's analyses are based upon a large and novel sample of hourly interval, metered natural gas consumption data. These real-world usage data are combined with available information about average hourly residential electricity loads, domestic electricity and natural gas rate tariff schedules, and hourly grid electricity GHG emissions intensities to deliver important insights about the potential for electrification efforts to contribute to electricity load growth, increase total household expenditures on energy, and achieve GHG emissions abatement.

2. Methods

2.1. Account level hourly gas use data

Account level hourly natural gas usage data were requested from Southern California Gas (SCG) for all residential accounts located within two target zipcodes: 91746 & 91732. These zipcodes comprise environmentally disadvantaged communities within the areas South El Monte, Bassett, and Avocado Heights, as determined from census tract level CalEnviroScreen 3.0 aggregate scores ($\geq$ 75*th percentile*) [23]. This sample was specifically selected to be representative of communities with high proportions of renters and low-income families - household types which are known to be the most challenging, but also among the most important, to reach through decarbonization efforts [24]. This data request was submitted through SCG's public Energy Data Access Program (EDRP) website on 6/18/2019 [25]. Following a

Table 1. Included attributes for SCG customers in the provided sample of customer hourly natural gas usage data.

Attribute	Description
BILL_ACT_KEY	Bill account key associated with each service address
MTR_BDG_NBR	Meter badge ID number
MTR_DESC	Meter type description (Individually Metered, Master Metered, etc)
DA_NBR	Service address house number
SVC_ADDR1	Service address street name and type
SVC_ADRR2	Additional service address information such as apartment numbers
SVC_CITY	Service address city
SVC_STATE	Service address state
SVC_ZIP	Service address 5-digit ZIP Code
RATE	Billing rate code

review period under the EDRP protocol and the signing of a non-disclosure agreement between SCG and UCLA, the request was successfully processed and the requested data released via a secure Electronic Data Transfer (EDT) portal on 9/25/2019. The usage data provided comprised one year's worth of usage for a total of (N = 17,072) individual households. The attributes included within the data provided by SCG are detailed in table 1. For all normalized energy comparison involving natural gas an energy unit conversion factor of (99,976.12 $Btu/_{US}Therm$) was used.

2.2. Static hourly electricity load profile data

Static hourly electricity load profile data computed from the sample of all Southern California Edison (SCE) residential customers was obtained from the SCE website for the 2018 & 2019 calendar years. Data files for these two years were concatenated and filtered to reflect the data collection period (8/8/2018 - 8/15/2019) for the sample of SCG usage data. For all normalized energy unit comparison calculations involving electricity an energy conversion factor of (3,412.14 Btu/kWh) was used. A discussion of the comparability of statistics derived from these two data samples has been provided in the supplementary material submitted in conjunction with this manuscript.

2.3. Electrical appliance energy efficiency gains

When evaluating the potential for electrification efforts to contribute to a daily peak electricity loads it is necessary to consider whether the electric versions of appliances might be more or less energy efficient. Previous work by Ebrahimi *et al* has characterized the range of end-use energy efficiency gains for available electrical alternatives to common residential natural-gas appliances [20]. Due to the uncertainties involving the technology implementation choices of future electrification efforts, we used this range efficiency values to calculate the best/worst case scenarios in terms of the average household wide efficiency gain expected from full house electrification. We then applied this range of efficiency factors to generate lower and upper bounds on the expected contribution of fuel switching to daily peak electricity load growth.

2.4. CAISO hourly GHG emissions intensity data

15 minute interval grid generation supply mix data were obtained from CAISO through the OASIS application programmatic interface (API). A nearly continuous time series was assembled for a nine year historical period spanning 1/1/2010 through 12/31/2019. There were a small number of days ($N < 15$) during this period for which information was not available through the OASIS API. GHG emissions intensity factors (kg CO_2/MWh) for each generator category were obtained from The Climate Registry for the relevant data periods [26]. Hourly average GHG emissions intensities were computed by applying generator specific factors to hourly generator output data and aggregating according to hour of day.

2.5. Electricity and Gas utility rate tariff data

bDomestic electricity rate tariffs for SCE were obtained from NREL's OpenEI utility rate tariff database [27]. The tariff schedules under consideration were restricted to SCE's currently available domestic TOU rates: *TOU-D-4-9PM*, *TOU-D-5-8PM*, *TOU-D-PRIME*. Domestic natural gas rate tariffs for SCG were obtained from regulatory filings: *SCHEDULE-GR* [28]. For natural gas, seasonal variations in fuel procurement costs were addressed by assessing the range of reported monthly procurement costs over the previous year. In order to enhance the comparability of rates between fuel types, only baseline tier consumption levels were considered. This was done to avoid the need to address differences in demand charges at successive consumption tiers between the two fuel types.

3. Results

3.1. Temporal patterns in residential gas use

Figure 1 contains a set of fan-plots which depict the average hourly natural gas use rates per household aggregated across the months in the year (a), the days in the week (b), and the hours in the day (c) observed within our sample of hourly interval natural gas usage data. This type of plot is useful for illustrating changes in the distribution of values across discrete periods in time. The quantiles of the distribution of natural gas use rates are broken into 5-percentile intervals, each of which is plotted as a continuous horizontal band of color. According to this convention, the top and bottom-most bands, which are shown with the greatest transparency, correspond to the 95th and the 5th percentiles, respectively. Similarly, the 50th percentiles, which correspond to the median values, are plotted as solid black lines.

The first subplot (figure 1(a)) shows, as expected, that average hourly rates of natural gas use are higher in winter months (December–February) than in summer months (June–August). What is interesting about this trend however, is the absolute magnitude of the variation in peak use rates between the different months. For example, in this particular year, the overall maximum use rates occurred during the month of February and reached levels which 2.5x higher than the highest rates of use observed at any time throughout the summer period. This degree of seasonal variation in peak consumption levels is larger that that which is commonly observed relative to residential electricity load profiles, even among households with heavy summer air conditioning use.

The second subplot (figure 1(b)) shows that on average, median rates of natural gas use tend to be somewhat higher during the weekend than during the work week. However, in the case of this trend, the magnitude of the differences are far less significant than the seasonal trends. Moreover, the minimum and maximum percentiles of average hourly use rates are fairly consistent across all of the days in the week. This indicates that the cadence of the common work schedule is not a hugely significant determinant of average rates of natural gas use within the sampled homes.

Finally, in the third subplot (figure 1(c)) there is significant diurnal variation in hourly natural gas use rates. This average hourly natural gas use rate profile is characterized by two two distinct peaks: one in the morning, beginning at 5 AM and tapering off around Noon, and then another in the evening, beginning around 4PM and then tapering off again around 9PM. Crucially, this pattern of variation almost exactly mimics the well-known pattern of diurnal variations in electricity demand.

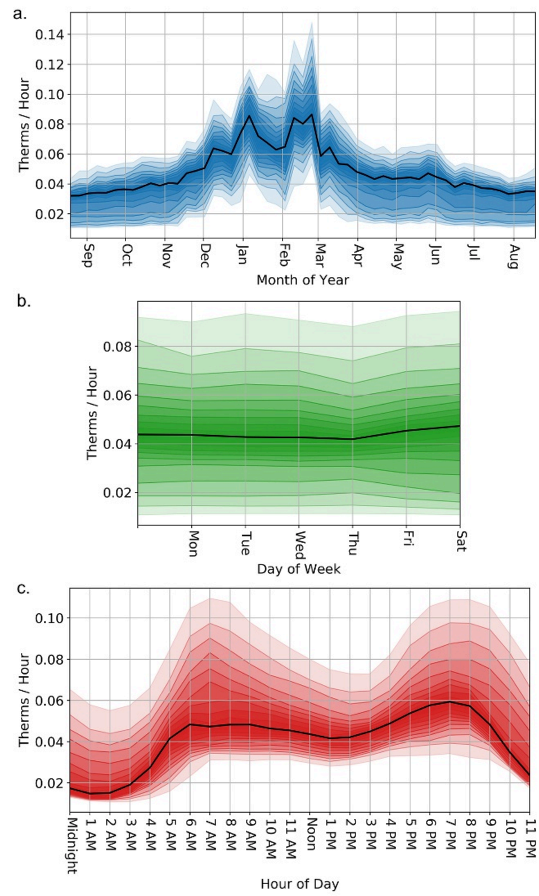

Figure 1. Fan-plots illustrating variations in monthly (a), daily (b), and hourly (c) patterns of average hourly natural gas usage rates computed for a sample of (N = 17,072) SoCal Gas residential accounts between 8/15/2018 - 8/15/2019.

3.2. Implications for peak electricity load growth

The first issue stemming from these observed patterns in hourly natural gas use relates to the potential for household appliance electrification to exacerbate peak electricity loads. Figure 2 contains a set of subplots which illustrate how the full electrification of the average residential household could potentially impact daily peak electricity loads. The first of these subplots (figure 2(a)) provides a direct comparison of daily peak energy demands for natural gas versus electricity for the typical residential household. This comparison is provided in standardized energy units of ($MMBtu/hr$). In the case of natural gas, the typical household represents an aggregation of use data collected from the 17,072 households sampled as part of this study. Conversely, in the case of electricity, the average household represents an aggregation of usage data collected from all of the residential service accounts throughout SCE's entire service territory. These data are made publicly available by SCE as part of CPUC regulatory reporting requirements.

As expected, daily peak natural gas loads were found to be largest during the winter months while daily peak electricity loads were found to be largest during summer months. More important that these seasonal variations however, were the relative magnitudes of the peak loads observed for each energy source. The average daily peak load for natural gas was (0.007135 $MMBtu/hr$). This is more than twice the average daily peak load levels calculated for electricity, at (0.003613$MMBtu/hr$).

The second subplot (figure 2(b)) provides an area plot depicting a range of percentage increases in peak daily electricity loads which have been calculated assuming: the full electrification of all existing natural gas end-uses and the application of a set of upper (75%—green) and lower bounds (17%—red) on the efficiency gain of electrified appliances. As this data shows, even with aggressive assumptions about the

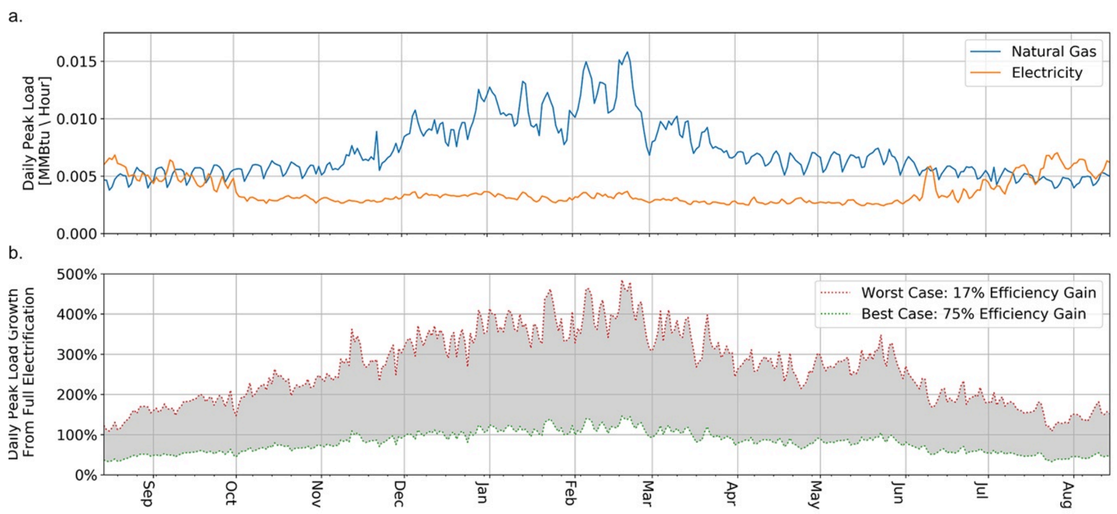

Figure 2. Line plot providing a unit standardized comparison of daily peak natural gas use for the average household within the SCG sample dataset relative to daily peak electricity loads for the average residential household within SCE service territory (*MMBtu*/*hr*) (a). Shaded area plot depicting the estimated range in the growth of daily peak electricity loads due to full household electrification calculated using best case upper (75%) and worst case lower (17%) bounds on the assumed overall efficiency of gain of a fully electrified household (b).

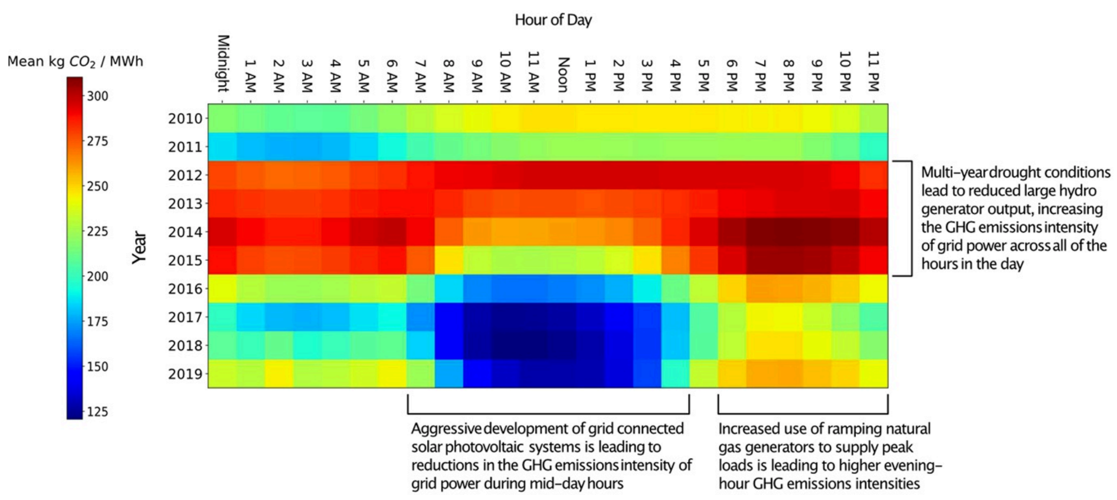

Figure 3. Heat-map illustrating variations in the average hourly GHG emissions intensity of grid sourced electricity within the CAISO balancing region for each hour in the day for the years 2010–2019. A multi-year period of anomalously high GHG emissions intensities, caused by drought related reductions in large-hydro generator outputs, are highlighted at right. Joint impacts of expanded solar PV output, stemming from the success of the state's RPS, as well as the increased reliance on natural gas thermal generators to supply ramping peak loads, are highlighted at bottom.

potential for energy efficiency improvements stemming from fuel switching, the potential impacts on daily peak electricity loads are likely to be dramatic. Under best case efficiency assumptions, full electrification is expected to increase daily peak loads, on average throughout the year, by 80%. Conversely, under worst case assumptions, daily peak loads are estimated to increase by an average of 265%.

3.3. Implications for GHG Emissions Abatement

A second issue involving the timing of residential natural gas use relates to the potential GHG emissions abatement benefits from undertaking widespread electrification. Figure 3 contains a heat-map which depicts year over year changes in the average hourly GHG emissions intensities ($kg\ CO_2/MWh$) of generators supplying CAISO's balancing territory between 2010–2019. The changing patterns of color in this figure reflect structural changes in the output of the regional grid's portfolio of generator assets - given the different characteristic emissions intensities of different generator types (thermal, hydro, solar, wind, etc). The first, most noticeable feature of this plot is the prominent discontinuity in the annual pattern of GHG intensity levels, visible as a prominent horizontal band of red colored cells spanning the period from 2012–2015. These years correspond to a multi-year drought which negatively impacted

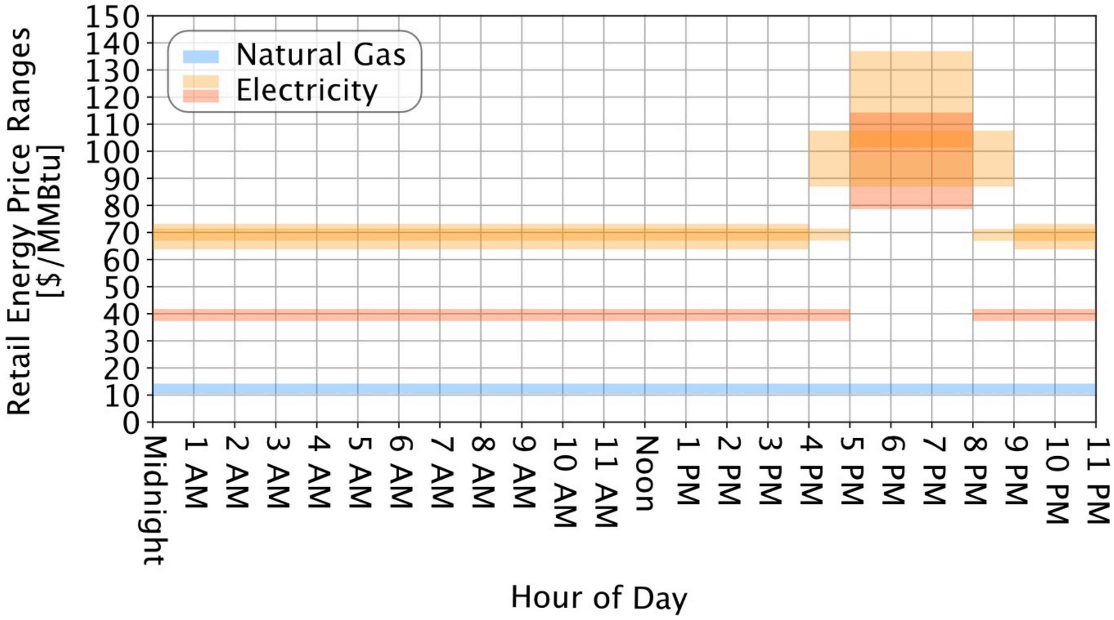

Figure 4. Comparison of local retail price ranges for electricity (red & orange) and natural gas (blue) using standardized energy units ($/*MMBtu*), by hour of day throughout the course of a year. These figures assume current residential rate tariff schedules and within-baseline-tier consumption levels. Note: the two different electricity rate tariffs depicted (red & orange) have different daily basic charges, minimum daily charges, and baseline credits. Thus, the range of values plotted only reflect the marginal cost of energy procurement.

the ability of the state's large hydro generating stations to supply power at nominal levels. This temporary loss of zero-emissions generator output was offset by the increased output of natural gas fired thermal generators possessing much higher GHG emissions intensities.

In addition to the impacts of the statewide drought, beginning in 2013, a significant shift in GHG emissions intensities during mid-day hours (10AM–4PM) becomes apparent in the circular collection of blue colored cells located in the lower portion of the figure. These changes reflect the rapid increase in the penetration of grid connected solar generation assets procured under the state's RPS during this period. Interestingly, and largely in proportion to these mid-day declines in GHG emissions intensities, corresponding increases in the GHG emissions intensities of grid power consumed during peak hours (6AM–9AM & 5PM–10PM) are also visible. These proportional increases reflect the increased use of rapid ramping peaker natural gas turbines to offset the predicable diurnal pattern of solar generator output.

This trend calls into question the extent of the GHG abatement benefits which are likely to accrue from electrification efforts in the absence of a fully decarbonized electric grid. As it stands, the GHG emissions intensities of electrical power consumed during peak hours are increasing year over year. These increases are due to the rapid decline in solar generator output each day being offset by rapid ramping in the output of natural gas fired peaker power plants. These plants' higher GHG emissions intensities are due not only to their fuel source but also due to design features required to facilitate their rapid ramp-rates and intermittent operation [29].

3.4. Implications for household expenditures on energy

The third potential implication from the timing of natural gas use relates to changes in the total annual expenditures on energy of households due to fuel switching. Current diurnal patterns in the average hourly GHG emissions intensities of grid power consumption are largely a product of parallel growth in renewable generation output and early-evening peak electricity loads. Among the efforts which have been undertaken to combat this phenomenon, commonly referred to as the *duck curve*, has been the introduction of a requirement for IOUs to implement new, mandatory default TOU rates for all of their customers [30]. This requirement, currently in the early phases of roll-out, means that residential customers who do not opt-out from the new default TOU rates, the price of electricity will fluctuate throughout the hours of the day, the days of the week, and the months of the year [17].

The complexity of these TOU rate structures have been intentionally designed to mirror the complexity of the dynamics between renewable generation output and consumer electricity demand, as previously discussed. An unfortunate result of this complexity however, is that it can be difficult to quantitatively assess what constitutes the *typical* or *average* annual expenditures incurred by a member of a given customer class. Figure 4, provides a rough comparison of the normalized cost of energy between electricity and natural gas for standard residential rate tiers. The horizontal yellow bands of color plot the range of electricity prices possible at each hour of the day - depending upon the day of the week and month of the year - under currently available residential TOU rate structures within SCE service territory. By comparison, the horizontal blue band within the figure, shows the price of natural within SCG territory, which does not vary by time-of-use. In both cases, the energy prices reflect levels of consumption occurring within the baseline tier.

As figure 4 illustrates, the prevailing cost of a unit of energy delivered in the form of electricity is at least 4–6x higher than for natural gas within this region. Moreover, under existing TOU electricity rate structures, the price premium for electrical energy can grow to a factor of 12x during peak hours (4PM–9PM). In the absence of significant future increases in the relative cost of natural gas, either due to changing market dynamics or external government intervention, it is likely the that the widespread electrification will result in an increase in total annual household expenditures on energy. This is due to the relative inflexibility of most work and educational schedules.

4. Discussion

On paper, California's three pronged approach to the decarbonization of its residential building sector makes logical sense. However, if the transition is to be successful in practice, policy makers will be required to navigate numerous potential pitfalls. Careful, integrated planning and sequencing of future electrification policies and programs will be necessary to avoid unintended consequences. The results of this study show, under current conditions, whole house electrification programs are likely to exacerbate daily peak electricity loads and increase total household expenditures on energy. Moreover, the state's continued reliance on natural gas peaker-plants means that these efforts will likely only produce modest GHG emissions abatement benefits.

There are a number of concrete strategies which can be adopted to address these concerns. First, regarding peak electricity load growth, electrification initiatives should initially target natural gas end-use appliances which have the highest expected efficiency gains and whose anticipated time-of-use least coincides with periods of peak-electricity demand. New, highly efficient, hybrid heat-pump based electric water heating technologies represent a significant opportunity in this regard. These systems are both more energy efficient than their natural gas based counterparts and also provide interesting opportunities for the use of thermal energy storage to decouple the timing of energy usage from the timing of energy service delivery.

Secondly, regarding the potential GHG emissions abatement benefits of electrification, it is critical that California expand requirements for the development of new energy storage capacity to absorb the growing surplus of renewable energy supply generated during certain periods [31]. Increasing the state's ability to store and redistribute renewably generated energy is essential to counteract the growing GHG emissions intensities of peak period grid power. IOU energy storage capacity procurement requirements must be expanded and elaborated. For example, new small scale distributed energy generation projects, such as rooftop solar PV systems, could be required to incorporate a minimum amount of diurnal energy storage capacity, equivalent to say four hours worth of the system's nominal rated power output. Alternatively, for larger facilities, such a grid scale wind farm, the coupled storage requirement could instead focus on seasonal capacity. Rule 21, which currently allows utilities to dictate the characteristics of generation assets seeking interconnection to the grid, provides a natural mechanism for the articulation of these types of detailed storage requirements [32].

Finally, regarding the potential for widespread electrification of natural gas appliances to increase total household expenditures on energy—it appears that some level of energy cost increases are likely to be inevitable as part of any transition to a fully decarbonized residential building sector. The crucial question is how to minimize these costs and ensure that they be equitably distributed among rate-payers. Low income households in under-resourced and environmentally disadvantaged communities are likely to have very little flexibility in terms of the timing of their end-use energy consumption. This is due to the fact that members of these communities typically have to engage in longer distance commutes to their places of employment and have less flexibility in their work schedules [24]. A well designed electrification program should provide incentives not only to help under-resourced community members to overcome the initial, up-front costs of purchasing new electric appliances but also with rebates or other mechanisms for reducing the ongoing marginal cost of consuming a more expensive source of energy.

5. Conclusions

Decarbonization pathways involving extensive electrification efforts will require unprecedented integration of natural gas and electricity systems planning and policy implementation in order to be successful. On the electricity side, California's establishment of a progressive RPS was pioneering and has stimulated dramatic expansion of renewable generation capacity. Yet, despite this success, there remains insufficient grid scale energy storage capacity. This growing storage deficit is diminishing the marginal value of future renewable generation investments required by the RPS.

Related to this issue, has been the dramatically expanded use of natural gas thermal generators to supply the state's large and growing peak electricity demands. The further entrenchment of these gas facilities is a pernicious problem and has been largely responsible for the imminent rollout of new default TOU rates for all IOU customers. Raising the price of electricity during peak hours will unevenly impact different customer classes due to differences in the ability to either reduce the volume of their energy consumption or shift its occurrence in time. Without policy measures which cause natural gas to become far more expensive, reflecting its true environmental and social cost in air pollution health effects and global climate change impacts, the price differential between TOU electricity and the use of natural gas for heating and cooking may be insurmountable. Moreover, it is likely that low-income residents of disadvantaged communities, who have the least flexible work schedules, the least access to high-efficiency appliances and energy management systems, and inhabit the most poorly insulated housing stock, will be most adversely effected by these changes.

Previous modeling assumptions about the extent to which the efficiency improvements gains of electrified appliances will be able to compensate for peak-load growth seem overly optimistic. An improved understanding of real world efficiency improvements, based upon the ex-post analysis of metered consumption data, will likely be necessary in order to accurately assess the long term energy cost implications associated with electrifying different natural gas appliances.

Finally, the extent to which renewable generation, demand response, and distributed storage technologies will able to resolve these issues remains uncertain. Recent efforts to simulate the performance of California's residential energy system under high penetration levels of these new technologies found that only 48% of the additional electricity load was able to be met by otherwise excess renewable generation due to misalignment between the timing of energy demand and that of renewable supply [33]. If these imbalances persist it will result in the need for addition grid capacity and the sustained production of GHG emissions.

All of these issues point to the need for the development of more integrated policy approaches to decarbonization, and perhaps, for measures to ensure that natural gas pricing reflects the fuel's true costs to society. Deep decarbonization of the energy system will require much greater investment in energy storage assets, delivered at multiple scales. Additionally, funds must be provided to directly support the participation of under-resourced communities in this transition. Failure to do so will dramatically limit the GHG reduction potential of electrification and exacerbate existing socio-economic disparities in access to high quality, low carbon energy services.

Acknowledgments

Financial support for this study was provided by a research grant from the California Energy Commission (EPC-17-050) as part of the project titled 'Using Big Data to Holistically Assess Benefits from Building Energy System Transition Pathways in Disadvantaged Communities'.

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