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Towards a smart and sustainable residential energy culture: assessing participant feedback from a long-term smart grid pilot project

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Abstract

Background: Smart grid tools (e.g., individualized disaggregated data, goal setting, and behavioural suggestions/feedback) increase opportunities to reduce or shift residential electricity consumption, but can they shape residential energy culture? And what underlying factors influence this shift? Insights are identified from a qualitative analysis of a 3-year residential smart grid project in a suburb of Toronto, Canada. Interviews evaluated whether participants experienced changes in their energy culture and identified underlying factors. In particular, the impacts of the project tools on participants' norms (attitudes and awareness towards energy management), material culture (technical changes) and energy practices (conservation/peak shifting actions) were assessed, and motivations and barriers towards energy management were identified. The effectiveness of engagement mechanisms (i.e., web portal, reminder emails, webinars, incentivized control programme, and weekly electricity reports) was also evaluated. By examining detailed qualitative feedback following a multi-year suburban smart grid project in Ontario this study aims to (1) assess the changes in energy culture over the duration of the 3-year project and to (2) assess the underlying factors influencing household energy consumption and a smart residential energy culture.

Results: Findings from the interview were compared to the results of an initial project survey to identify longer-term influences on energy culture. Increases in self-reported awareness and practices were accounted for, with the web portal and individualized weekly feedback email reported most frequently as causes of change. While increased awareness was obtained, participants needed additional guidance to make substantial changes. Although participants were financially motivated, norms of lifestyle and convenience, as well as competing household values of energy management were the largest barriers to home energy management.

Conclusions: This study showcases challenges for engaging homeowners with home energy management technologies due to norms as well as competing household interests. Nuanced findings as an outcome of this study framed around energy cultures can influence future studies on smart grid engagement and consumer behaviour with larger samples sizes. In particular, future studies can further investigate the motivations and barriers surrounding residential energy cultures, how to engage different 'cultures of consumption' within households, and elements to effectively educate consumers beyond disaggregated feedback.

Keywords: Conservation and demand management (CDM), Demand-side management (DSM), Energy cultures, Feedback, Household engagement, Smart grid, Time of use (TOU) pricing

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Background

Consumer engagement and the smart grid

Residential smart grid infrastructure incorporates two-way flows of electricity and information from the utility to the consumer and back; thus, changing the typical roles of utilities and consumers [1, 2]. Smart grid technologies allow for both smart control and user-centered control and can facilitate the integration of household appliances for scheduling and management [3]. This enables 'demand-side intelligence', facilitating increased real-time electricity cost and consumption feedback to consumers to increase their awareness and energy management to achieve a more sustainable residential energy culture [4, 5]. As a result, the smart grid provides opportunities to reduce and shift residential electricity consumption, which can decrease the financial, environmental, and social costs of the electricity supply. The influence of smart grid infrastructure in enabling electricity conservation and demand management (CDM) is widely proclaimed in literature and policy [6, 7].

Various jurisdictions have experienced the development of a smart residential energy culture through smart grid technology deployment. Savings of approximately 7–13% have been experienced in advanced residential smart grid projects in North America, Australia, and Japan [8]. A variety of smart grid tools—mechanisms to engage consumers with the smart grid system and smart meter data—can be deployed. These tools allow users to view data and optimize appliance use for household electricity management (e.g., mobile or web applications, goal setting, and appliance control mechanisms). Additionally, many customers see positive value from smart metering, which can lead to successful technological adoption [9]. As a result, smart metering technology brings an opportunity to shift consumers towards a smarter and more sustainable energy culture [5] through the adoption of new technologies and efficiency measures, shifts in energy practices, and changes in norms surrounding energy management.

However, the implementation of technology is not the sole contributor to changes in energy behaviours, consumer engagement is also required to establish a culture of CDM. Temporal patterns of energy consumption are highly influenced by consumer behaviour and involve attitudes, awareness, and actions towards energy CDM [10–12]. Consequently, the end-user is the key variable in the prediction of smart grid system success [13]. Energy is 'doubly invisible' since it is an intangible force and governed by unobtrusive habits, which makes it difficult to promote CDM behaviours without increasing awareness [14]. The parallel delivery of behaviour change programmes, alongside the installation of advanced metering infrastructure (AMI), is vital for successful implementation and to gain benefit from the system [11]. Therefore, the smart grid policy must also include provisions for engagement mechanisms.

Complexities of consumption, behaviour, and technical transitions

Transitions in the smart grid incorporate actors at different scales. These sociotechnical innovation transitions involve artifacts, knowledge, resources, capital, and the interaction of human actors at multiple levels [15, 16]. State intervention and policy reform are often mandatory within sustainability transitions [17] and new conceptualizations of innovations to incorporate user practice across space and time are needed [18]. Therefore, studying detailed user perspectives on smart grid technologies can develop the understanding of niche actors [19].

Household energy consumption is also complex and is influenced by internal and external factors [20]. Differences between identical residential units can be up to 200%, with household behaviours contributing to this extreme variability [21–24]. Behavioural theories view several factors as critical influences, including attitudes, norms, agency, habits, and emotions [25, 26]. Household energy use is also positively correlated with household income [12, 20, 27] and household size [12, 28, 29]. Education levels [22, 30] and energy literacy [23, 29] as well as economic profile [28, 29] positively correlate to the willingness to conserve and invest in efficiency upgrades. In regards to age demographics, households with younger members are more willing to invest in new and efficient technologies [22]; however, household dynamics and competing attitudes may influence the overall level of conservation [12, 28, 29]. Although these socioeconomic factors contribute to household energy consumption, additional technical, social, and behavioural factors remain. Habits, routines, and behavioural practices have a strong influence over the use of efficient technologies [22]. Behaviours contribute to two thirds of household energy use, compared to structural and technological components [31]. Therefore, behavioural 'wedges' are also required to change how consumers use technology and operate household systems to result in consumption shifts [24]. Understanding these complexities can give insights for changing energy behaviours.

Complexity in changing energy behaviours

Influencing energy consumption through behavioural interventions has been studied at length in the literature. Encouraging CDM behaviour can be achieved through antecedent interventions, which occur before the behaviour (e.g., goal setting, information, and commitments) or consequence interventions, which provide either rewards or penalties after the behaviour has occurred (e.g., feedback and rewards) [10]. Feedback can be a key method in changing energy behaviours through individual or comparative feedback [32]. Information-based strategies have experienced average savings of 7.4% [33]. However, changes in energy beliefs or attitudes, not just knowledge, are required to change energy practices [34, 35]. Multiple types of engagement mechanisms are available and it is essential to assess participant feedback on different smart grid tools to improve our understanding of smart grid engagement and behaviour change potentials. Additionally, it is important for social science research to move beyond studies of hierarchal levels of change and investigate the dynamics of energy practices through new frameworks [18].

Energy cultures: a framework for a detailed understanding of energy use

Since factors influencing energy consumption remain complex and incorporate elements within both personal and contextual domains [20], utilizing frameworks to organize these nuances can highlight important details. Stephenson et al.'s [5] energy cultures framework provides a scalable framework to organize iterative self-reinforcing energy behaviours influenced by social and technical factors [36].

The energy cultures framework has been utilized in a variety of contexts, including: photovoltaic adoption [19], transportation and mobility [37–39], timber technologies [40], higher education energy behaviours [41], and residential energy interventions [42]. The energy cultures framework, however, has not been applied to the Canadian context, nor has it been applied to the smart grid; therefore, this pilot project extends the application of the energy cultures framework to the Canadian residential smart grid.

In this framework, widespread energy behaviours, otherwise called 'energy culture', are impacted by the interaction of three key elements. Firstly, material culture, involves household technologies, appliances, and building materials influencing energy use. Secondly, norms, involves the standards or expectations influencing energy consumption that exist at individual and societal scales (e.g., thermal comfort and convenience). These norms are influenced by beliefs, knowledge, and motivations towards energy consumption. Thirdly, energy practices, involve household activities and processes related to energy consumption [5, 36, 43]. Practices and skills involve the uptake of technology and materials allowing routinized behaviours [19]. In the energy cultures framework practices include infrequent actions, a key differentiating factor from practice as outlined in social practice theory [36]. This conceptualization of energy practices complements this pilot project's focus on whole-house energy management, where both repetitive and infrequent energy actions could influence household consumption (e.g., changing thermostat settings, setting automation functions, setting goals, etc.). External contextual factors (e.g., structural, technical, economic, socio-economic, climactic factors) are also included in the energy cultures framework [44]. Overall, the energy cultures framework is scalable [37] and can be applied to the smart grid context.

Applying the energy cultures framework to the smart grid

As emphasized by Strengers [45], simply relying on a technologically-driven smart utopia is problematic; instead, elements of user adoption and consumption patterns need to be incorporated through social science approaches [46]. Utilizing the comprehensive approach of the energy cultures framework [5, 36] allows these user constructs to be reimagined and to move beyond individual practices through the investigation of in-depth household decision-making and energy culture. Mallett et al. [47] identify the influence of technological perceptions and adoption in the smart grid context, where policy makers should utilize awareness of the local context in the design of smart grid technology and policies. As a result, the energy cultures framework can provide useful framing for understanding the complexities surrounding energy use [37].

As outlined in Fig. 1, transitioning to a smarter and more sustainable residential energy culture involves multiple elements. It involves a change in culture, behaviour, and technology, influenced by markets and policy [19]. Firstly, an aspirational shift towards increased energy management through flexibility in consumption patterns, acceptance of technological management and efficiency upgrades, and increased willingness to reduce consumption. Secondly, this transition involves an 'upgrade' in material culture through installing smart grid and smart home technologies, increasing building envelope and appliance efficiencies, and using other home energy management technologies (e.g., control, optimization, and automation) [48, 49]. Thirdly, this transition involves adhering to practices that reduce consumption, shift to off-peak periods, and align with reduction goals. This includes the use of automation, optimization, and energy management technology, as well as a change in routinized and infrequent consumption actions to shift towards the aspired smart and sustainable energy culture. Thus, the transition involves a change in norms, an adoption of technology, and a shift in actions, which is being attempted in Canada, particularly in the province of Ontario.

Ontario's smart grid

The province of Ontario is a leader in smart grid deployment in Canada and aimed to shift its provincial energy culture as a result of substantial changes in technology,

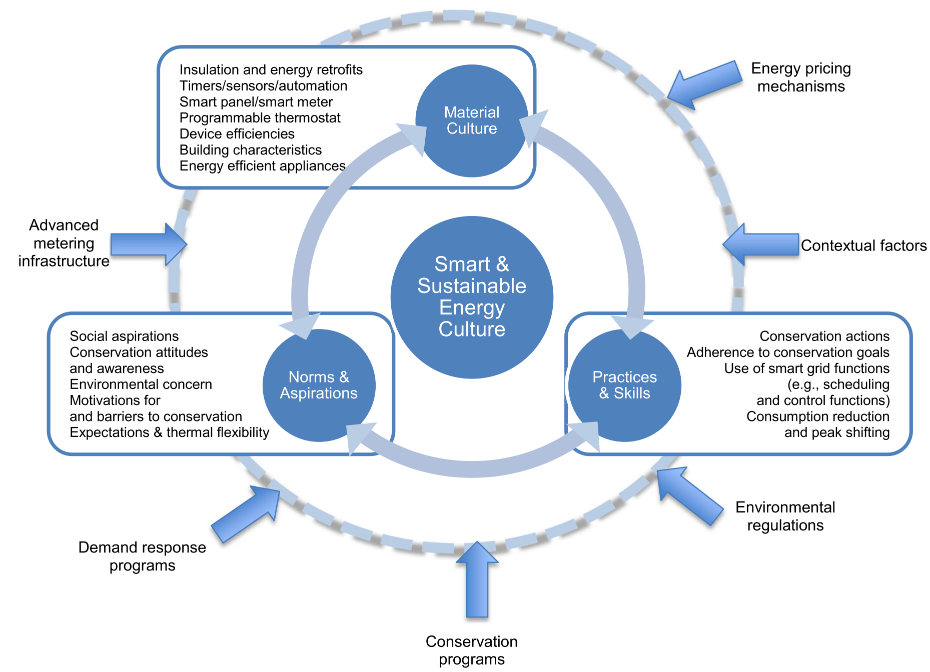

Fig. 1 Smart residential energy cultures framework, adapted from [5, 36]

policy, and market rules [1, 50, 51]. The smart grid is a key element of the province's electricity CDM policies and was first highlighted in the province's *Electricity Act, 1998*. As part of Ontario's 2004 Smart Metering Initiative, 4.8 million smart meters were installed, resulting in the first and largest Canadian smart meter deployment [50]. This allowed time-of-use (TOU) pricing to encourage off-peak consumption. Ontario's 2013 Long-Term Energy Plan adopted a Conservation First policy involving consumer engagement through smart meter demand response methods to achieve long-term targets [52]. As a result, studies of smart grid engagement mechanism effectiveness in Ontario are critical for the successful implementation of smart grid technology and the achievement of CDM targets.

Several elements have established Ontario's leadership in Canadian smart grid development. Ontario has fully operationalized AMI, new rate options (TOU pricing), and has partially implemented demand response for load shifting or ancillary services [53]. Further, distributed energy storage for peak shaving, self-healing grids, microgrids, and voltage reactive power control are under study within the province [53]. Consequently, Ontario is the largest actor in the Canadian smart grid landscape. Local distribution companies facilitate the interaction of the smart grid between the utility and the consumer, and in particular, standardized electricity data are accessible to approximately two thirds of Ontario customers for better management and understanding of energy consumption [1, 53]. Therefore, Ontario's phases of smart grid development included a multitude of technological implementation, funds, policies, and mechanisms at multiples scales (Table 1). Opportunities remain to examine details regarding how these externalities can shape residential energy cultures.

To better understand the complexity of residential consumer behaviour in the smart grid, this study utilizes a qualitative approach to study the impact of smart grid technologies on participants' energy culture [5, 37] within a 3-year residential smart grid pilot project. This study aims to (1) determine whether the project influenced the participants' energy culture and to (2) determine what factors influenced 'smart' energy management and project engagement. Since this study focuses on the agency of the individual, we utilize the energy cultures framework to gain a detailed understanding of the complexity and the nuances surrounding residential energy behaviours [19].

Methods

Project overview and research objectives

Twenty-five households in Milton, Ontario were involved in a 3-year residential smart grid project to manage their electricity use. This included the installation of a smart panel, which provided circuit-level feedback and monitoring [54]. The utility company recruited these households to this opt-in programme by email; therefore, these participants could be considered 'early adopters' of smart grid technologies by showing interest in this programme. Throughout the project, 13 types of interactions were implemented from June 2011 to March

Table 1 Elements of Ontario's shift to the smart grid and conservation culture [1, 50, 53]

Objectives	Technology	Funds and initiatives	Policies	Additional mechanisms	Actors
Peak shifting, conservation, peak shaving, system efficiencies and security, distributed generation, integration of new technologies, privacy, efficiency, customer value, coordination, reliability, flexibility, and innovation	Established: smart meters and AMI and integration of renewables Testing: energy storage self-healing grids and microgrids and voltage reactive power	Smart Grid Fund and Green Button Initiative	Green Energy and Green Economy Act	TOU pricing and demand response	Ministry of Energy, Ontario Energy Board, Ontario Power Authority, Independent Electricity System Operator, Hydro One Networks, and local distribution companies

2014. These mechanisms had multiple purposes (e.g., administrative, behavioural, technical). This paper focuses on six behavioural engagement mechanisms (Table 2).

Understanding the impact(s) of these mechanisms on residential energy cultures can aid in the development of similar programmes, policies, and smart grid infrastructure. This paper applies Stephenson et al.'s [5, 36] energy cultures framework to provide insights, to discuss engagement mechanism feedback, and to highlight factors influencing participants' energy culture throughout the pilot project. This study investigates the impact of the engagement mechanisms on residential energy culture (material culture, norms, and energy practices) as well as the identification of factors influencing the adoption of a smart energy culture (motivations and barriers) through qualitative feedback obtained from 15 participating households.

The aims of this study are twofold: (1) to identify whether the project influenced participants' energy culture and (2) to highlight what factors influenced the adoption of a smart energy management culture within the participating households. The first aim will be met by assessing the changes in attitudes and awareness towards energy management as well as changes in practices and material culture throughout the project. The second aim will be met by examining the major motivations and barriers influencing participants' energy management.

Data collection and analysis

The pilot project was located in Milton, Ontario, a suburb approximately 50 km west of Toronto [54–56] (Fig. 2). Key elements of this town are its rapid population growth, high economic status, and the dominant residential building type (Table 3). This remains consistent with the participant group (Table 6). This study involves an analysis of the participant feedback collected throughout the 3-year pilot project (Table 4). In particular, data from both an initial project survey and an interview near the end of the project were utilized to assess participant feedback and energy culture at the beginning and end of the pilot project.

Survey data

Participants were asked to complete an initial project survey at the beginning of the project. Collected online through an email, this survey involved a series of Likert scales to measure the baseline factors contributing to the household profile and energy management. This survey involved baseline data collection related to the households' socioeconomic profile, household structural,

Table 2 Description of the project-led behavioural engagement mechanisms

Item	Description	Classification	Frequency	Timeframe
Goal setting	Self-set goal for consumption reduction monitored on a web portal	Goal setting	Ongoing	December 2011–project end
Web portal	Web-based portal providing access to whole house and appliance-level consumption feedback. Access to settings for scheduling, goal setting, and control also included	Feedback, monitoring, and control	Ongoing	November 2011–April 2012
Reminder emails	Bi-monthly emails sent to remind participants to log in to the web portal	Reminder	Bi-monthly	January 2012–August 2013
Webinar	A webinar to introduce the control feature and other elements of the web portal	Education	Once	March 2013
Incentivized control programme	Households were invited to use the air conditioner 'control' function in return for C$100 for each week's participation for 2 weeks during the months of July and August 2013	Control	Twice	July and August 2013
Weekly electricity report	A weekly email sent to participants indicating their total, on-peak, and appliance-specific consumption. It compared their consumption to other households in the project as well as to the previous year. Conservation tips were provided	Feedback	Weekly	June–December 2014

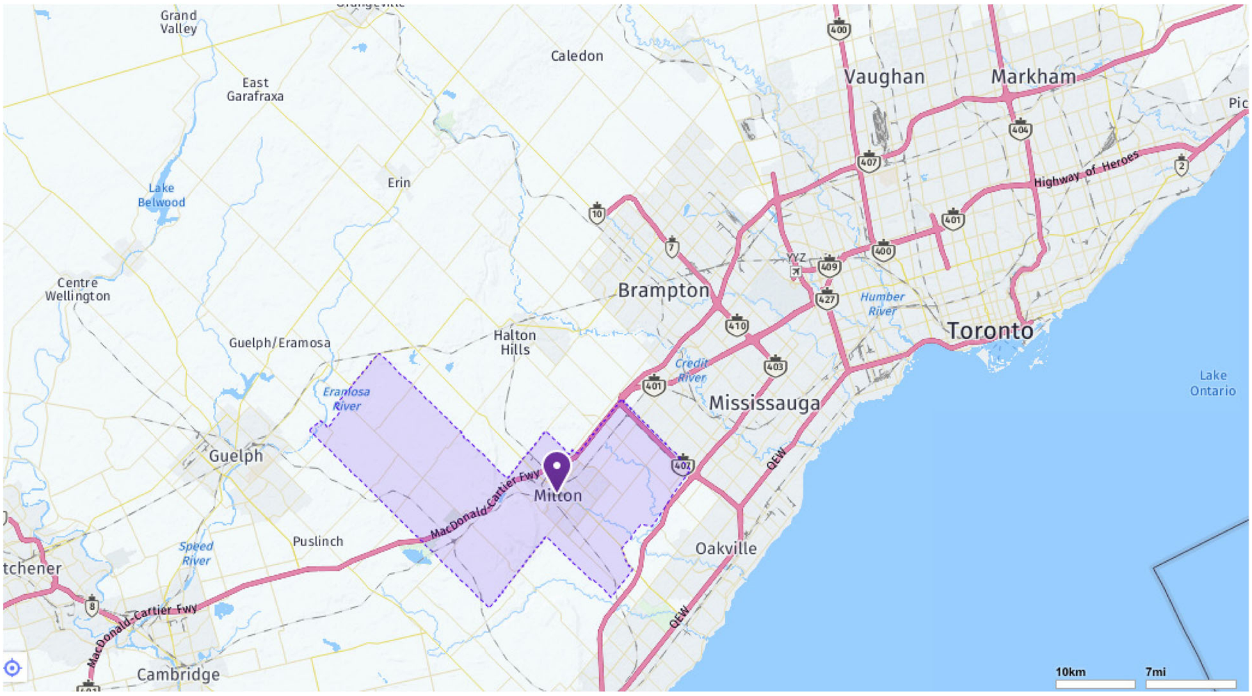

Fig. 2 Milton, Ontario map in proximity to Toronto [98]

and technological profile as well as motivations, attitudes, actions, awareness, and goals towards energy management. The information collected through this survey was used for the baseline elements related to household materials, practices, norms, and contextual factors.

Interview data

To gather qualitative data for this study, structured interviews were conducted with project participants near

Table 3 Key socio-economic statistics of Milton, Ontario [86, 99]

Attribute	Value
Land area (square km)	363
Population density (per square km)	232
Average age (years)	33
Dominant dwelling size by number of bedrooms	3 bedrooms
Average household size by number of people	3
Population 2011	75,880
Population 2016	101,715
Percentage population growth 2011–2016	34%
Dominant residential building type	Single-detached house
Average income (before tax) CAD	$49,229
Average household income (before tax)	$106,743
Dominant education level	Postsecondary certificate, diploma, or degree

the end of the project. Structured interviews provided detailed feedback and responses that aligned with the previous survey and followed up on the motivations, attitudes, actions, awareness, and goals related to household energy management. The interviews involved close-ended (e.g., Likert and rating scales) and open-ended questions (e.g., rationales and description of experiences with project elements). The initial project began with 25 participants who opted-in to the programme after an open call for participants by the utility; however, seven households had exited the programme and were not available to interview. Out of 18 potential interviews, 15 were completed for analysis, resulting in an 83% response rate. One researcher coded the interview transcriptions using NVivo based on the main themes of the research: attitudes, awareness, motivations, and barriers related to energy management; energy management practices and actions; and engagement mechanism feedback.

For further engagement mechanism feedback, participants were asked to rate the effectiveness of the project engagement mechanisms on a scale of 1 to 5 (not effective to very effective). The term 'effective' was defined as providing the participant with the necessary knowledge to actively participate in the project and to influence their energy culture.

The motivations for and barriers to energy management identified through the interviews were coded using topic-specific codes (e.g., lifestyle, convenience, cost).

Table 4 Details and procedure for participant feedback and involvement

Element	Method	Total sample	Timeframe	Analysis
Initial project recruitment	Email and participant opt-in	25 joined the programme	Project start	Not applicable - this recruitment email did not involve data used for analysis
Initial survey	On-line web survey	12	Project start	Quantitative coding of responses
Interview	In-person semi-structured interviews	15	Year 3	Qualitative coding of transcribed interviews using NVivo quantitative comparison between responses from the interview and initial survey

Upon completion of coding the interviews, frequency counts of each topic-specific code were calculated, and the seven most cited motivations and barriers were determined and presented in the results.

Comparing changes between the beginning and end of the project

To compare initial and final project findings on the residential energy culture, the ratings of statements in the interview were compared to the ratings in the initial survey. Participant baseline attitudes, motivations, objectives, and actions towards energy management were evaluated. The percentages of households that had increased, decreased, or kept the same rating were calculated and summarized in the results. Only 12 of the 15 households participated in both the initial survey and the interview, which were used for comparative analysis.

In the initial survey and the interview, participants were asked how strongly they agreed with statements regarding their attitudes, awareness, and energy actions towards energy management in their home by rating them from 1 to 7 (strongly disagree to strongly agree) (Table 5).[1] In the interview, participants were also asked to rate their perceived levels of awareness, attitudes, and actions towards energy management before and after the project on a scale of 1–5 (low to high).

Existing participant contextual factors

Household energy cultures are influenced by a multitude of factors including the structural (i.e., built environment and technologies) and socioeconomic contexts (i.e., education and income) [44]. The context is an important consideration in the energy cultures framework [19, 44]; thus, in this section, we discuss the contextual factors of the participants. The dominant building type can be classified as 'new suburban build' and detached two storey (Table 6). These houses had large living areas, with the majority of houses sized 1500–2999 ft^2. Although the participating houses were built between 1970 and 2010, most of the houses were built after 2000 (Table 6). Consequently, these households had newer and more efficient structural elements and appliances. Therefore, limited upgrades were expected in the material culture (e.g., appliances, building envelope, energy systems, heating and cooling technologies). The households had higher levels of income ($80,000 to $150,000+) and education (Bachelor's or beyond). These contextual factors are consistent with the overall Town of Milton population statistics (Table 3).

Household typologies

The success of the smart grid involves various actors and typologies of end-users [13]. Classifications of users in technical infrastructures are crucial for the development of energy policies and programmes [57]. The application of typologies in the energy cultures context is limited and has only been applied by Lawson et al. [58]. Although this typology could be useful for detailed qualitative analysis, it does not include smart grid considerations. Therefore, smart grid typologies considering materials, norms, and practices alongside the smart grid context were used in this analysis. To further understand the profiles of the 15 participant households, Gaye and Wallenborn's [59] typology of smart grid users for home energy management was used. This typology was selected due to its ability to capture elements aligned with Ontario factors of energy consumption in relation to the smart grid, particularly thermal flexibility, electricity management, environmental motivations, and technology.

By assessing the motivations and barriers towards energy management and project participation, the four categories (economist, environmentalist, technicians, compromiser)

Table 5 Awareness, attitude, and action statements from the interview and initial survey

Awareness statements	
1	Currently, I am aware of how much electricity is used by my electric appliances
2	Currently, I am aware of how much money it costs to use each of my electric appliances
3	Currently, I am aware of the carbon footprint associated with using each of my electric appliances
Attitude statements	
4	I believe that it is important to conserve as much energy in my home as possible
5	I believe that it is important to reduce my electricity usage during on-peak times as much as possible
Action statements	
6	I try to conserve as much energy in my home as possible
7	I try to reduce my electricity usage during on-peak times as much as possible

Table 6 Household profiles of interview participants

Household	Number of children (0–17 years)	Number of adults (18–64 years)	Total residents	Year house built	Type of house	Approximate house size (ft^2)	Household income (before taxes)	Highest education in household
1	0	3	3	1970–1979	Detached two or more storey	1500–1999	$150,000+	Bachelor's degree
2	1	2	3	2000–2006	Detached two or more storey	3000–3499	$150,000+	University certificate or diploma below bachelor level
3	2	2	4	2007–2010	Detached two or more storey	2500–2999	$150,000 and over	Master's degree
4	2	3	5	2000–2006	Detached two or more storey	1500–1999	$60,000–$69,999	Bachelor's degree
5	2	2	4	2000–2006	Detached two or more storey	2500–2999	$125,000–$149,999	Bachelor's degree
6	2	2	4	2000–2006	Detached two or more storey	2000–2499	$150,000+	Degree in medicine, dentistry, veterinary medicine, or optometry
7	1	2	3	2007–2010	Detached two or more storey	2500–2999	$90,000–$99,999	Bachelor's degree
8	3	2	5	2000–2006	Detached one storey	1500–1999	$90,000 - $99,999	University certificate or diploma below bachelor level
9	3	5	8	2007–2010	Detached two or more storey	2500–2999	$150,000+	Bachelor's degree
10	2	2	4	2000–2006	Row housing (attached on both sides)	1000–1499	$90,000–$99,999	Non-university certificate or diploma
11	4	2	6	2000–2006	Semi-detached two or more storey	2000–2499	$80,000–$89,999	Bachelor's degree
12	2	2	4	2000–2006	Semi-detached two or more storey	1500–1999	$90,000–$99,999	Bachelor's degree
13	1	2	3	2007–2010	Detached two or more storey	2500–2999	$150,000 and over	Bachelor's degree
14	2	2	4	1970–1979	Detached two or more storey	1500–1999	$125,000–$149,999	Bachelor's degree
15	0	2	2	1970–1979	Detached two or more storey	2000–2499	$150,000 and over	Bachelor's degree

were applied to the participating households. A majority of the interview participants (8) can be classified as 'economists,' as their main motivation for management was to save money while maintaining their lifestyle and comfort, and they had low thermal flexibility. This aligns with typical Canadian comfort standards, considering space heating constitutes the majority (63%) of residential energy usage in Canada [60]. These households were not willing to sacrifice household comfort and convenience to benefit the environment. The remaining households (7) can be classified as 'compromisers' where technology was an important aspect of increasing their awareness to reduce consumption while being motivated by economic and environmental concerns for current and future CDM actions. It should be noted that there were no 'environmentalists,' as participants did not view environmental protection as their sole and primary motivation for energy management. Additionally, no households were categorized as 'technicians'. Thus, only 'compromiser' and 'economist' households were identified in this study.

Limitations

It should be noted that the intensity of support and capital cost of the technology utilized in this pilot project resulted in sample size limitations. The pilot initially had 25 participants, but by later stages of the multi-year pilot project, 15 participants remained active and willing to participate in the interview. Small sample sizes are predominant in smart metering pilot project studies, especially those with intrusive technologies similar to this pilot project and similar sample sizes have been observed in the peer-reviewed literature in regional contexts beyond Canada [61–63]. Despite this limitation, the interviews provided a detailed understanding of household decision-making and feedback on long-term residential smart grid engagement mechanisms. Consequently, the following results provide valuable insights for residential smart grid research that can be extended with larger samples.

Research contributions

As noted by Abrahamse et al. [10], relatively little is known about the long-term effects of smart grid engagement mechanisms on energy behaviour. Existing studies have focused on short-term impacts (≤ 1 year) and initial engagement [8, 33, 64, 65]. Long-term studies (˃ 1 year) can identify whether interventions encourage sustained behaviours as well as household temporal rhythms of energy consumption [35, 66–68]; thus, they are important for smart grid intervention and energy culture studies. Additionally, previous studies that focus on the influence of engagement mechanisms for energy CDM do not include a comprehensive set of smart grid technologies [12, 32, 69–71]. This research provides holistic insights on factors contributing to household energy culture and interaction with multiple smart grid engagement mechanisms over multiple years. Consequently, this study articulates the nuances surrounding initial engagement and re-engagement to assess shifts in the energy culture of participating households.

This study acknowledges the complexity and interconnectedness of societal behaviour and understands that studying change requires the exploration of these complex environments [19]. Since this study focuses on the agency of the individual, we utilize the energy cultures framework to understand the complexity surrounding residential energy behaviours. This paper extends beyond a critique of public engagement practices by delivering in-depth understanding on household decision-making by utilizing the energy cultures framework [72].

Results and discussion

At the beginning of the interviews, participants were prompted to reflect on consumption changes during the project and participants shared a wide range of responses. Upon exploring factors influencing changes, a detailed understanding of household energy consumption and energy culture was gained. These nuances are outlined in the following sections: "Changes in awareness towards energy management", "Changes in attitudes towards energy management", "Changes in energy management practices", "Changes in material culture", followed by a discussion of the main "Motivations and barriers influencing smart energy management".

Changes in awareness towards energy management

This project aimed to increase awareness towards energy management through multiple mechanisms, including the web portal (disaggregated feedback), a weekly newsletter (individual and normative feedback), and webinar (information and education). The majority (73%) of respondents indicated that their awareness had increased due to multiple project interactions, specifically, the web portal, weekly electricity report, and the webinar, due to the information provided. As participant 6 mentioned, "When we actually monitored the web portal, we would be surprised at how much the dishwasher uses, so that I would try to run the dishwasher either less frequently or during off-peak hours […] you just don't think about it until you actually see it." Respondents who reported the same awareness levels (27%) provided rationales such as already having a high level of awareness or project disengagement.

Participants were asked to rate statements regarding their energy CDM awareness in both the initial survey and the interview (Table 5). In comparing the responses, a trend of increase in awareness can be observed; however, awareness of electricity use and associated costs of consumption were raised more than awareness of the carbon footprint associated with electricity use (Fig. 3). This corresponds to the trends reported in the interview for increased awareness, as stated above, and the motivations for energy management reported later in this paper.

Information and feedback can stimulate conservation and peak shifting in residential households [73, 74]; however, studies have also highlighted mixed-results with information provision [71]. The results of this study highlight increased self-reported awareness towards energy management particularly the energy used and associated costs, due to feedback and information gained throughout the project. Individualized, disaggregated feedback was provided through the web portal, whereas the weekly electricity report provided normative feedback, increasing awareness of their position among their peers. However, as similarly articulated in the literature, the linear approach of the information deficit model is limited and additional factors need to be assessed [14, 75].

Changes in attitudes towards energy management

Attitudes towards energy CDM are important to energy policy development, as ineffective policies can be a result of unaddressed attitudes [76]. More than half (53%) of participants reported improved attitudes towards energy management during the programme due to multiple project interactions, specifically the web portal and the weekly electricity report. In particular, participant 15 found the engagement mechanisms improved their attitudes towards CDM due to "seeing how much is wasted by poor decisions every day. Especially leaving stuff on. There's a lot of things that will use power when you're not even here." The 47% who stated their attitudes remained the same provided rationales including existing CDM attitudes, cultural background and upbringing, and the inability of the project to change their priorities.

In comparing the attitudes from the initial survey to the interview, the average ratings for statements on conservation and peak shifting remained similar and at a high value from the beginning to end stages of the project. Participants viewed shifting and conserving energy as important throughout the project (Fig. 3). External influences and technologies can influence attitudes and perceived behavioural control [25, 26]. Similarly, these results reveal that increased insights and information stimulated positive attitudes towards household energy management and engagement. Social and cultural factors are highly related to energy consumption and adoption of technologies and management [77]. As seen in this project, homeowners might already have 'highly conservative' attitudes towards their energy management; however, their knowledge about CDM opportunities may be limited. The engagement mechanisms utilized provided a means to reinforce positive attitudes within these households to influence elements related to their energy culture, as articulated in the following sections.

Changes in energy management practices

To assess the impact of the project on household energy practices, households were asked to assess their level of actions towards household energy management before and after the project. Similar to changes in awareness, self-reported increases in actions over the project period were highlighted by a majority of participants (53%). Multiple project interactions, particularly the web portal, weekly electricity report, project tools, and thermostat scheduling were identified as helpful for changing practices. The information provided in the interactions resulted in a more proactive approach to household energy consumption. In particular, participant 11 mentioned that they used the information to "see what [they] have done, and see the difference [in consumption]." Those who reported the same level of action, 47% were either already energy conscious, lacked knowledge for reductions, or were concerned about comfort. Like participant 9 who noted "I changed, but not as much as I could have [...] because there are a number of things that I could still do." This highlights how certain

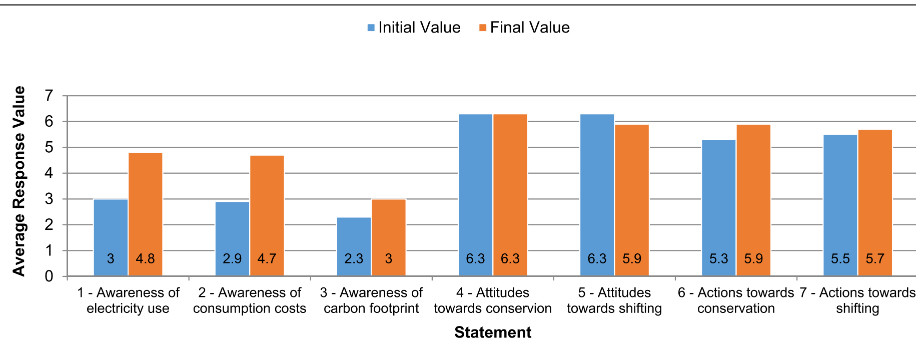

Fig. 3 Awareness, attitudes and action statement ratings in the initial survey and final interview. Average response value, on a scale of 1–7 (strongly disagree–strongly agree), $n = 12$

barriers, discussed later in this paper, can inhibit the adoption of smart energy management practices.

Perceived energy management practices before and after the project remained high. Participants were asked to rate two statements regarding their energy management actions in the initial survey and the interview (Table 5) and similarly high ratings indicate that participants actively used conservation and peak shifting practices throughout the project (Fig. 3). Changes in practices involved shifting discretionary loads to off-peak, using thermostat programming and appliance timers, highlighting changes in rhythms of consumption [77], and increased energy management [48]. However, limited project devices for management (e.g., control, appliance scheduling) were used. Overall, participants valued direct control over their energy management and this was restated during the interviews.

Participants who indicated increases in management highlighted project participation increased their knowledge of possible actions (Table 7). These results highlight the ability of these engagement mechanisms, particularly the web portal and weekly electricity reports,

Table 7 Summary of household changes in the level of energy management practices

Household	Change in energy management practices	Energy practices	Rationale
1	Increased	Off-peak use of appliances and overall conservation efforts	Awareness through reminders and increased knowledge of TOU periods
2	Same	Did not change	Convenience and lack of knowledge
3	Same	Small conservation actions where possible and thermostat control	Did not know what to do
4	Increased	Programmed thermostat, tried to reduce during on-peak times, adjusted thermostat by 2 °C, and thermostat control and optimization	Increased awareness, access to tools to make changesBarrier: cannot afford the newest and most expensive appliances
5	Increased	Spent more time being energy conscious, turned off lights, tracked and turned off appliances, and utilized timers on lights and appliances	Access to consumption data
6	Increased	Ran appliances off-peak, turned off lights, turned off devices not in use, and thermostat control	Increased awareness
7	Same	Ran major appliances off-peak, used timers on laundry machine, and thermostat control	Already energy conscious and increased number of people in the home
8	Same	Small actions that did not influence comfort and thermostat control	Same actions and attitudes and already energy conscious
9	Increased	Programmed the AC, purchased and used fans, changed daily behaviours related to energy, and used timers on smart appliances	Technology available (programmable thermostat) and increased awareness
10	Same	Unplugged items, replaced bulbs and appliances, shifted to off-peak periods, overall conservation actions, and thermostat control	Same actions and attitudes and already energy conscious
11	Increased	Responded to TOU periods (e.g., laundry on evenings and weekends)	Project interactions
12	Increased	Overall conservation and reduced consumption of high-consuming appliances and responded to TOU periods	Increased awareness
13	Same	Reduced consumption of high consuming devices, responded to TOU periods, and thermostat control	Same actions and attitudes and already energy conscious
14	Same	Turned off devices not in use, investigated circuit loads for reductions, responded to TOU periods, and thermostat control	Comfort
15	Increased	On-peak consumption and overall consumption reduction, used automation technology to help with day-to-day reductions, and thermostat control	Visualization of information

to increase perceived CDM actions by households through information provision. Although increased information has mixed effects on consumption changes in the literature [35, 78, 79], these qualitative findings highlight perceived shifts in participants' energy management practices related to feedback provision, and thus increased consumption awareness, as previously articulated. An opportunity is created for future research to analyze the impact of reported increased awareness and action levels on consumption levels.

Changes in material culture

Throughout the programme, participants had opportunities to upgrade their material culture. As previously mentioned, the majority of participating homes were 'new suburban build,' with limited opportunities for large efficiency upgrades; however, some material culture changes were noted (Table 8). Upgrades were mostly limited to small-device replacements (e.g., lighting), appliance replacement (e.g., washer or dryer), or related to larger household improvements (e.g., basement renovations). Similar to Attari et al. [80], households perceived curtailment actions (e.g., turning off lights, reducing the use of appliances) as more attainable than energy efficiency improvements. Further, some households identified socioeconomic pressures (i.e., income and affordability) and contextual factors (i.e., home ownership) prevented efficiency upgrades, aligning with previous studies [12, 20, 27–29].

Despite the newer home build, some households did make notable changes in their material culture, including smart home devices and automation technologies, solar panels, smart appliances, and large device removal (e.g., servers). There were even changes in actions related to practices. For example, some participants purchased and increased the use of fans during the evenings instead of the air conditioner. Participants identified financial and conservation concerns and increased awareness as motivations for material culture changes (Table 8).

Motivations and barriers influencing smart energy management

To conclude the assessment of factors influencing participants' energy management and overall energy culture, the motivations to and barriers for project participation in energy management actions were investigated. As articulated by Mackenzie-Mohr et al. [81, 82], understanding motivations and barriers for particular behaviours can provide detailed understanding for targeting behaviours and creating effective engagement programmes. Further, these motivations and barriers can highlight underlying factors (both internal and external) influencing the overall energy culture [19, 36, 40].

Table 8 Summary of household changes in material culture

Household	Changes in material culture	Renovations
1	Replaced light bulbs, washing machine, and dryer	Upstairs bathroom; lower bathroom; main bathroom
2	Installed new computer, pot lights, and a television	Basement - pot lights and TV
3	Installed appliances related to new basement: gym equipment, computer, and TV/entertainment centre, and a new printer; replaced light bulbs; installed smart home automation	Basement - added home theater, gym, and office; installed smart home automation
4	Replaced light bulbs; installed new HVAC system	Not applicable - no renovations took place
5	Replaced TV, light bulbs, dishwasher, backdoor; installed light and appliance timers and solar panels	New back door; installed solar panels
6	Installed a hot tub	Not applicable - no renovations took place
7	Replaced light bulbs	Not applicable - no renovations took place
8	Installed additional freezer; replaced TV, light bulbs, and appliances	Not applicable - no renovations took place
9	Replaced washing machine and dryer (more efficient and with timers) and light bulbs; installed light and appliance timers	Not applicable - no renovations took place
10	Replaced light bulbs	Not applicable - no renovations took place
11	Replaced dishwasher and light bulbs; installed light and appliance timers, motion sensors, and ceiling fans	Not applicable - no renovations took place
12	Installed new TV; replaced light bulbs	Renovated basement
13	Replaced light bulbs	Not applicable - no renovations took place
14	Installed hot tub, extra TV, small fridge in basement; replaced washing machine and light bulbs; installed ceiling fans	Installed solar panels
15	Removed multiple large servers; replaced and added new fridges; replaced light bulbs and HVAC system; installed weather stripping, light and appliance timers, and motion sensors	Installed smart home and automation technology; completed home energy audit

To assess how underlying motivations changed over time, the motivations for participation identified in the interviews were compared to the original motivations reported in the initial survey. Some motivations remained at similar levels while others decreased over time (Fig. 4). The motivations to save money and to reduce the amount of energy consumed were rated the highest by most respondents at the end of the project. This further emphasizes the value of financial feedback for these households. As participant 3 stated:

> "[…] I am not a big 'save the planet' kind of person […] I'm a 'save money,' kind of person. Which, ultimately at the end of the day yields the same result; because electricity costs money, and if you're saving in one area then you're saving in the other."

For many participants, reducing their carbon footprint did not resonate with them, like participant 4, who "[did not] even know what that was." Participant 11 stated, "I don't correlate with that at all […] it is not a factor." Therefore, engaging homeowners through 'carbon footprint' feedback was not broadly effective to achieve shifts without an educational component to the programme. Interestingly, an increased and equally high rating was given to 'trying a new web-based energy management technology' at the interview, indicating a positive experience since the start of the project.

Further, 38 barriers to project participation and energy management were identified throughout the interviews and consolidated into general themes (Table 9). The main barriers were lifestyle and convenience, whereas the main motivations for energy management were to save money and to receive more feedback and information on their consumption levels.

These barriers and motivations influenced the engagement with mechanisms throughout the project. Participants were asked to rate the effectiveness of the engagement mechanisms experienced in this study, with the results summarized in Fig. 5. It is clear that certain mechanisms were perceived more positively than others; however, certain motivations and barriers related to home energy management influenced these perceptions. The following sections outline main motivations and barriers for home energy management and how they influenced engagement with behaviour-based project interactions (the web portal, the weekly electricity report, goal setting, webinar, reminder emails, and the incentivized control programme).

Table 9 Main motivations for and barriers to energy management

Rank	Barriers	Motivations
1	Lifestyle	To save money
2	Convenience	Information on consumption
3	Technical issues with the system	Increased awareness
4	Family members	Reduce energy consumption
5	Time	Moral obligation
6	Did not know how else to reduce their consumption	To better respond to time of use prices
7	Lack of flexibility	To reduce environmental impact

Barriers: lifestyle and convenience

Throughout the interviews, participants highlighted lifestyle and convenience as substantial barriers for utilizing these smart tools for energy management. Certain participants were not willing to give up their standards of comfort, such as participant 8:

"I'm not going to change a whole lot. I'm aware that we have to run things at different time periods, because trying to have it running at peak hours when everybody else is using it can result in the brownout. So I know that's going to happen, but people have to live, and they have to use their stuff whenever they can."

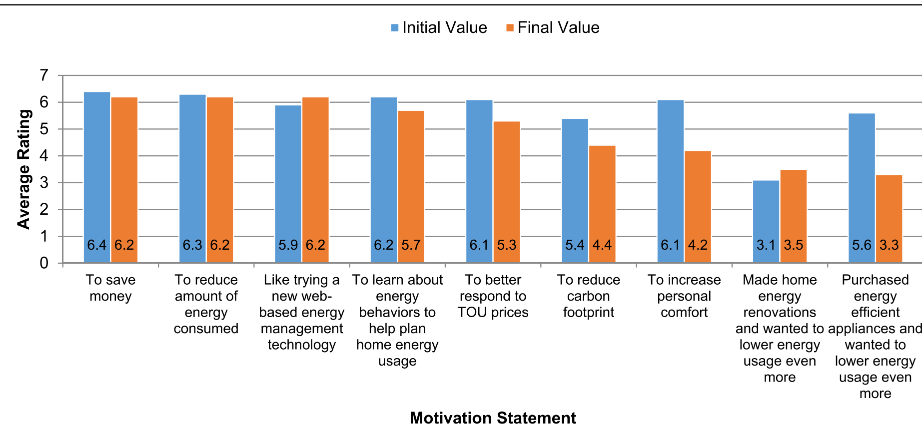

Fig. 4 Motivation ratings at the initial survey and final interview. Averages of ratings on a scale of 1–7 (strongly disagree to strongly agree), $n = 12$

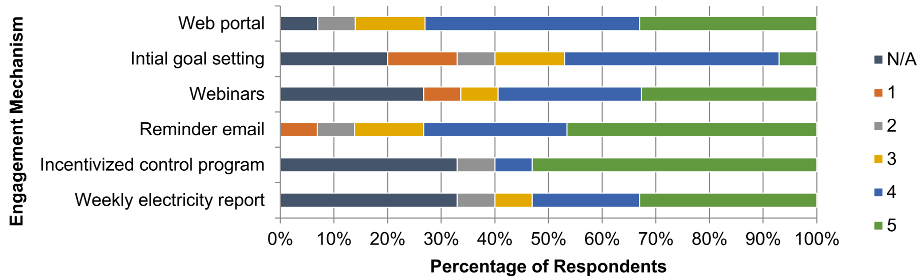

Fig. 5 Engagement mechanisms effectiveness ratings by percentage of respondentsRated on a scale from 1 to 5 (not effective–very effective), $n = 15$

Interestingly, for some, standards of comfort overrode motivations to save costs, such as participant 9 who articulated, "just because you know convenience and comfort is more important than on-peak time is. Because I need to use it during the day because it easier, I will just go ahead and use it during the day. Even though I know it's costing me more, I am just going to do it."

For others, it was a matter of using appliances when it was most convenient for them, due to their busy schedules or large families, such as participant 11 "if we need them we need them […] Being a stay-at-home mom and running a business out of the house, is a little different." These values of convenience are considered barriers to energy consumption changes [83, 84].

The barrier of convenience was highly articulated in the lack of acceptance and use of the scheduling function. This feature promoted peak shifting practices for discretionary loads through circuit control. Nearly half (46%) of the participants used the scheduling function for energy practices of their thermostat and appliances. Since the scheduling feature conflicted with lifestyle (e.g., people being home during the day), it was perceived as ineffective for energy CDM. Some participants mentioned they would override the feature, showing how norms of convenience inhibited the use of this energy management tool. For example, participant 2 mentioned, "After a while it was unclear […] what the benefit was. Because if I want to use the dishwasher, I will use the dishwasher." The participants who did not use the scheduling function chose so due to convenience. As indicated by participant 12, "I am not so sure when you would use the scheduling function. Because we use [our appliances] when we find it convenient. So I left it off and I never used it." Therefore, norms were the largest barrier to the acceptance of this smart home energy management practice.

Although the project provided opportunities for scripting behaviour through technological changes, household standards for energy use remained prominent barriers to engagement. Personal obligations related to lifestyle and comfort were highly valued and highlight a challenge for engagement to reduce the consumption of 'invisible' resources [84]. The participant feedback aligns with Leadbetter and Swan [85], where appliance control has limited abilities to modify demand before negatively impacting comfort. This emphasizes how norms can highly impact energy practices and the adoption of smart home energy management tools.

Barriers: technical issues and preferences

Another set of substantial barriers to participation was technical issues. In particular, these participants identified accessibility issues and difficulty in learning to use the web portal. This was also the case for the scheduling function, including accessibility issues for making quick setting changes. Many respondents expressed preferences for mobile web applications with 'push notifications' instead of a passive portal only accessible by computer. In particular, participant 15 stated:

> "The worst part for me is not having access to the web portal in as many forms as necessary for me. A site that would work on your phone when you're running around doing stuff would be great. It would be really interesting to just jump in and see how your house is doing, or if you're you're going on the train and you just want to look at some graphs because you're thinking about something. That was really difficult to do on the web portal. I think that is the part that would need the most work [...]"

Consequently, technical issues limited participation in smart energy management.

Barrier: family members

As a contextual factor, household profiles were identified as a substantial barrier to energy management. As identified by Ford et al. [19], contextual factors can considerably influence the energy culture. Household changes were identified through the interviews and most households expressed consumption fluctuations due to household population changes. Households experienced certain family members entering or leaving the home, including members home during peak periods (Table 10).

For example, participant 9 highlighted competing norms and attitudes towards energy management with in-laws living in the home: "There are more adults in the house so it is hard to[…] I guess we could communicate that, so it's really our fault […] so it takes that flexibility away. Like more people are using things now." When asked about whether their attitudes reflect those of others in the home, participant 9 further identified "No […] because they do not pay the bill […] it is honestly because we have not really talked about it that much. It all comes down to balancing convenience versus efficiency." Participants with growing families were involved in this study, where 5 out of 15 homes experienced childbirth during the study. This is consistent with the Milton area, which had a population growth of 34% between 2011 and 2016 [86]. Those with newborns and adults home for childcare emphasized the importance of maintaining comfort during this time. As a result of changing profiles, homes experienced changes in norms and practices surrounding energy management.

Household dynamics and competing attitudes may influence the overall conservation [12, 28, 29, 87], so this was probed in the interview. A majority of participants (60%) expressed that CDM attitudes and actions were the same across household members. However, 27% said that the adults in the household had similar actions and attitudes, while the children did not. Since 13 participating households had children (between 0 and 17 years), it highlights an opportunity to engage children/teens in this study group to adjust their norms and to improve their energy practices. Existing studies have highlighted tremendous opportunities for residential energy savings by engaging children [87–89]. Interviewees mentioned possible engagement techniques, including a 'kids web portal', to engage their children, as well as relating their child's consumption to their allowance and activities. Although these contextual factors may be specific to the participants' circumstances, they highlight a substantial factor influencing consumption.

Barrier: time

Participants highlighted that energy management became secondary due to more pressing issues requiring their time, which is consistent with barriers observed in other residential energy cultures studies [42]. As indicated by participant 11, certain issues became more important: "Just [issues] happening at the house […] and dealing with the extra stress. Lots of stuff has happened, that is beyond the control of anything so this sort of takes the back burner for some of it."

Additionally, mechanisms requiring additional time to operate and learn to use, or did not align with their time, were not utilized, further highlighting the social challenge of coordination and strong values of convenience inhibiting energy management among households [84].

Table 10 Summary of changes to household population

Participant	Change in household population	Energy usage influence	Change to the number of people home during peak hours
1	Two adults moved out	Less consumption	2 less people
2	1 child born	Increased peak-hours consumption	1 adult and 1 infant—on maternity leave
3	No changes	No changes	No changes
4	No changes	No changes	No changes
5	1 child born and 1 adult home for childcare	Increased peak-hours consumption	1 adult and 1 infant—working from home
6	No changes	No changes	1 less adult—went from part-time to full-time work
7	1 child born and 1 adult home for childcare	Increased peak-hours consumption	1 adult and 1 infant—on maternity leave
8	1 less adult—adolescent moved out	Increased peak-hours consumption for TV and stove	1 less adult—stopped working from home
9	2 adults moved in	Increased peak-hours consumption	1 child and 2 adults home during the day
10	No changes	No changes	No changes
11	1 more adult and then 1 less adult	Increased fluctuations in consumption due to changes	1 less child—went to school
12	Change in work schedule	Used computer when home	1 adult worked from home (6 months)(used computer)
13	1 child born and 1 adult home for childcare	Increased peak-hours consumption	1 adult and 1 infant—on maternity leave
14	School schedule	Increased peak-hours consumption during the summer	Children home during summer (4 people home) and 1 adult—childcare during summer
15	No changes	No changes	No changes

Therefore, due to competing interests, participants' efficiency measures were not prioritized.

Barrier: lack of knowledge and skills to make additional changes

The lack of knowledge and skills for making additional changes was clearly articulated as a barrier to energy management. In particular, this barrier was strongly related to the goal setting function. Goal setting is identified as a promising form of antecedent intervention [10]. Although 80% of the respondents set goals, three-quarters of these respondents found goals ineffective due to the lack of knowledge to set and meet goals. As participant 3 noted, "I don't know what a proper goal would be. And then again steps to achieve them." Participants also mentioned that they were not motivated to change when unable to meet their goals. As participant 7 stated, "from an initial standpoint, it was hard to know where to start because you don't really know where you were, and what it translated into, in terms of where you wanted to be." Another respondent, participant 15, identified how difficult it was to reach their goals, "I remember setting my goals and quickly realizing that I was never really going to make them." Lack of knowledge is consistent with barriers in other energy cultures studies [42]. Providing additional guidance was suggested as a key area to reduce this barrier.

In this study, self-determined goals caused confusion and disengagement. This contradicts McCalley and Midden [69], where self-determined goals were more successful than assigned goals. External factors, such as low electricity prices, may limit the willingness to set and monitor goals in jurisdictions, such as Ontario, with on-peak prices of C$0.161/kWh at the time of the project [90]. Although participants identified that their awareness had increased, careful consideration for engaging consumers on *how* to make additional changes was needed in regards to goal setting.

Barrier: lack of flexibility

As a result of high standards for comfort and convenience, and household contextual factors, participants indicated a lack of willingness to make substantial changes in practices. Consequently, limited use of mechanisms for energy management (e.g., scheduling and control functions) occurred. Participants who did not utilize the thermostat control function mentioned concerns about flexibility and accessibility of the settings, similar to participant 3 who said:

> " I know they wanted to take over my thermostat […] I'm sorry, but I refuse to let that happen. Because you know what they talk about doing this automatic optimization, whether shutting on and off appliances so I can and cannot use them […] With two kids, I cannot deal with that. So I think part of it is my inflexibility […]"

This highlights the challenge of changing conventions and expectations [84] of homeowners in order to adopt home energy management technologies.

Motivation: to save money

As articulated earlier, households' financial motivations strongly influenced their overall energy culture. Participants highly valued that consumption feedback was provided in financial terms (consumption could be shown in kWh, dollars, or $kgCO_2$). As noted by Delmas et al. [15], information on monetary savings can be useful for engagement. In particular, financial feedback motivated participants to make changes in both material culture and practices. Increased information on appliance consumption costs provided households with opportunities to increase their savings by switching to off-peak periods, as well as to remove appliances. For two households, this meant removing servers contributing to higher energy bills (Table 8). Consequently, increased financial information led to some changes in material culture and energy practices, specifically peak shifting.

Motivation: increased consumption information and awareness

Participants highlighted the value of gaining more information consumption data and the ability to see historical appliance-level consumption through the web portal. This aligns with Chen et al. [91], who found that high-granularity consumption feedback can help to facilitate energy conservation. The importance of awareness and increased information was discussed thoroughly by participants in relation to the weekly newsletter electricity report, which provided a summary of household-level consumption as well as comparative feedback (average and best quintile). As participant 15 mentioned, "[…] it was really nice bites of information based on information from your account that did not require you to log in to the web portal." Others also liked that it was 'very high level'. As noted by Delmas and Lessem [74], comparative feedback can create social norms for electricity usage, and the combination of public and private feedback can lead to energy savings of up to 20%. The frequency of the electricity reports allowed households to see end-use impacts of their actions. Participant 11 reported, "The weekly piece that lets me know how I've done was very effective […] it was not until then that we really started paying attention." However, those participants with larger households or who operated home businesses considered it inappropriate to be compared to 'average' consumers. Presenting household consumption on a 'per person' measure for comparative feedback was suggested.

This highlights how weekly electricity reports aligned with participants' motivations for changing consumption, providing information comparing the household consumption to others (average and best quintile), along with energy saving tips, engaged consumers, and increased their consumption awareness, thus influencing participants' energy culture.

Instilling a smart energy culture beyond the pilot project

All interviewees identified the continued importance of managing energy consumption beyond the project, aligning with their previously articulated motivations, including saving money, improving efficiency, and reducing waste and environmental impacts. Additionally, participants throughout the interviews mentioned their willingness and desire to continue utilizing disaggregated feedback to understand their energy use. In particular, participant 6 moved to a new home without this technology and identified interest to install similar technologies to increase awareness and opportunities for management:

> "[Looking at] our first hydro bill [at our new home] I almost vomited, thinking how is that so much money? Because the house was heated floor in the kitchen, which we didn't have at the other place, so my thought was like, did someone turn it on? And then the kids were playing with the controls? And then I was like did someone turn it on and leave it? And, if I have it on all winter how is it going to impact our energy, I have no idea. There's no way to see it. So we were happy to move, but we were not happy that we were unable to monitor our usage at all [...] it was a very positive experience."

This highlights an example of how one household's energy culture shifted during the programme due to increased awareness and management, facilitated by smart technologies, only to readjust when moving to a different home with different material culture and contextual factors. Further, during the programme, two households installed more advanced home automation and smart home optimization technologies (Table 8). Participants valued this technology to improve their consumption awareness and their potential for increased energy management, therefore highlighting a few cases of an aspirational shift in household energy culture.

To reduce the main barriers discussed, programme elements for conserving energy should not interfere with lifestyle and convenience by being accessible, timely, and concise. For example, participants became disengaged with project mechanisms, such as scheduling and goal setting, if they were 'inconvenient' or interfered with their lifestyle. In addition, participants mentioned a need for a mobile web portal application, along with 'push' notifications for alerts of approaching goals or on-peak hours.

To maximize the key motivations, smart grid engagement mechanisms for these particular individuals can be aimed at providing 'money-saving' tips or alerts through reducing consumption or transitioning to off-peak consumption. Providing more direct feedback on particular strategies for CDM could also aid in reducing the barrier of not knowing how to improve. Setting this into the broader context of Ontario's smart grid development, important considerations can be made and tested with larger cohorts of participants, including the provision of disaggregated and real-time feedback utilizing financial data and control, scheduling, and optimization functions.

Conclusions

This study applied Stephenson et al.'s [5, 36] energy cultures framework to understand detailed nuances of household energy behaviours during a multi-year residential smart grid pilot project. This is the first pilot project to utilize the energy cultures framework in both a Canadian and smart grid context—extending the application of the framework both technologically and geographically. Additionally, the depth of qualitative feedback from the 3-year pilot project and the multiple engagement mechanisms used to engage and re-engage participants allows for further understanding of household decision-making processes in regard to energy consumption. In this project, participants increased their awareness and practices towards energy management. However, minimal changes in material culture took place due to the 'new suburban build' classification of the homes.

Key findings indicate that although these smart grid early adopters were interested in using this form of smart grid technology for managing their energy consumption, contextual factors and normative standards of lifestyle and convenience strongly inhibited the adoption of both a smarter and more sustainable energy culture within these households (Fig. 6). In particular, low energy prices and high standards of comfort resulted in less flexibility for shifting and reducing energy practices. Additionally, the range of household energy cultures within a house, and the fluctuation of household members, caused additional difficulties in changing practices. Although consumption awareness was gained, there remained a large lack of knowledge on how to make substantial and lasting changes in the home, which is consistent with other energy cultures studies [42]. In particular, households identified that more hands-on help would have been beneficial. Although a combination of tailored information goal setting and feedback

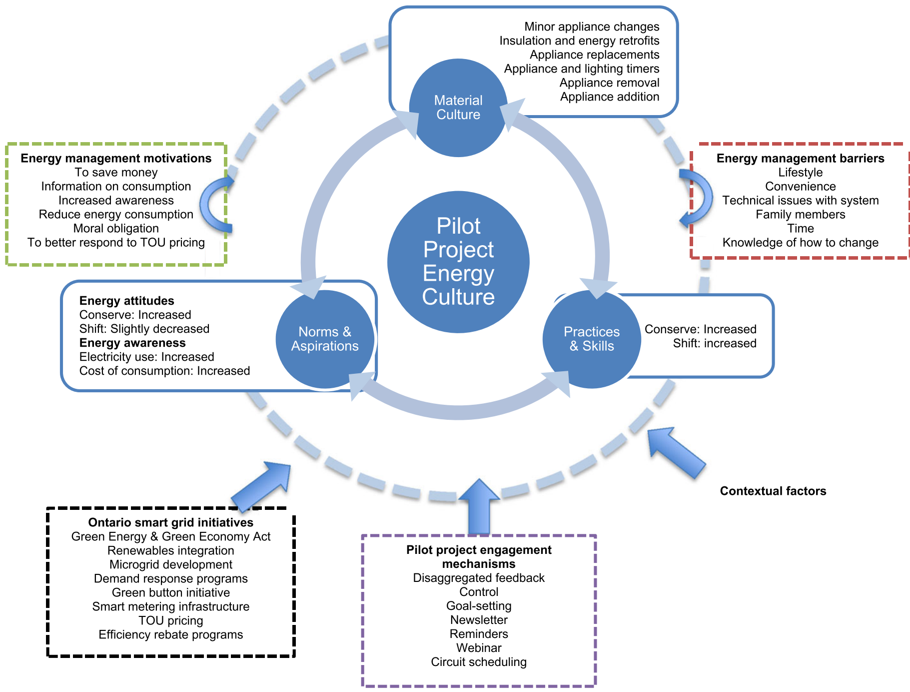

Fig. 6 Summary of changes in and influences on participant energy culture experienced during the pilot project. Adapted from [5, 36, 42]

was used in this pilot project, which is considered effective in the literature [71], it was not enough to substantially change participants' energy culture towards smarter and more sustainable energy management. Competing motivations and barriers reduced the perceived effectiveness of these mechanisms and overall management. These insights derived from a small-scale pilot project highlight some important nuances that may be missed in larger studies.

Outcomes from this pilot project highlight some of the challenges for changing longer-term energy practices and uptake of smarter energy management. Consumers, although motivated to make changes and to save money, can also be motivated by 'stone-aged psychological biases', such as self-interest, short-sightedness, status, social imitation, and ignorance of problems [92]. These conventions and personalized standards can inhibit change in practice and materials [84]. This reinforces the importance of integrating social and technical approaches for conservation approaches [84, 93, 94]. Thus, opportunities exist to extend beyond behavioural theories and intervention approaches to conceptualize the complexity of sociotechnical factors influencing household energy consumption, such as the energy cultures framework.

As Ontario is the most advanced province in AMI establishment across Canada, influenced by both landscape and regime level factors, it is important to look into these niche-level forces involved in the uptake of 'smarter' energy practices. The smart grid transition has been driven by the increased capabilities facilitated by the revolution in information and communication technologies as well as the increased emphasis on reducing energy-related climate change impacts [95]. However, particular attention needs to be paid to the engagement of consumers with these technologies to create long-lasting socio-technical change at the societal level [71, 96, 97]. Although the landscape factors of policies and infrastructure may support an AMI-driven energy culture, consumer norms need to support the uptake of additional changes in practices and material culture to facilitate smarter and more sustainable household energy management. Therefore, using a scalable framework for studying niche-level adoption factors that goes beyond consumption levels can provide detailed nuances related to energy consumption in particular areas. Gaining a deeper understanding of regional contexts is integral for smart grid policy development [47], thus further studies focusing on these nuances with larger participant groups can be beneficial for smart grid development in Ontario and other jurisdictions.

Endnotes

[1]These scales were created at the beginning of the pilot project for initial data collection and were continued in this study for consistency and evaluation of changes.

Abbreviations
CDM: Conservation and demand management; TOU: Time-of-use

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Availability of data and materials
Interview data are not available for publication, due to the required procedure for storing interview data approved by the University of Waterloo Research Ethics Committee (ORE # 19565).

Authors' contributions
This research was a result of work and collaboration between multiple authors. BL, PP, and IHR designed the interviews. BL led the writing of the paper with significant contributions from PP and IHR. All authors read and approved the final manuscript.

Ethics approval and consent to participate
This study and its interview questions were reviewed and received ethics clearance through a University of Waterloo Research Ethics Committee (ORE # 19565).
Before the interviews took place, an information letter about the interview and its ethics approval was provided to participants. Each participant signed a consent letter in order to participate in the interview.

Consent for publication
All interview participants provided written consent to allow for any comments provided in the interview to be used within the research results and within any relevant publications, with the understanding that any quotations would be anonymous. The University of Waterloo Research Ethics Committee approved this consent form (ORE # 19565).

Competing interests
The authors declare that they have no competing interests.

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