Energy Research & Social Science 50 (2019) 73–81

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Robotic vacuum cleaners save energy? Raising cleanliness conventions and energy demand in Australian households with smart home technologies

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ARTICLE INFO

Keywords:
Smart homes
Smart home technologies
Home automation
Social practices
Consumption
Energy efficiency
Digital homes
Household practices
Cleaning
Sustainability

ABSTRACT

The 'digital revolution' of household life is underway, with technologies such as robotic vacuum cleaners (robovacs) increasingly common. Various other automated appliances are emerging and being adopted in pursuit of the 'smart home'. Current discourses include assumptions and explicit claims that smart homes will be energy efficient and therefore more environmentally sustainable. However, smart home technologies are also presented as affording lifestyle enhancements in the areas of comfort, cleanliness, convenience, entertainment and security. Focusing specifically on one smart device – the robovac – this paper aims to demonstrate how visions of cleanliness in the smart home could be counterproductive to energy reductions and household wellbeing. We draw on a content analysis of smart home marketing and articles, and conversational interviews (involving home tours) with early adopters of robovacs and smart home technologies in Australia. We find that these devices may escalate conventions of cleanliness in the home and invite supplementary energy consumption. The paper concludes by providing suggestions for how energy stakeholders can respond.

1. Introduction

The 'digital revolution' of household life is underway, with technologies such as robotic vacuum cleaners (robovacs) and other smart or automated appliances already commonplace in many parts of the world. Recent robovac models feature internet connectivity and smartphone app control that enable the device to run automatically based on a pre-set schedule. More broadly, smart home technologies (SHTs) enable automation and remote control of many aspects of the home via digital interfaces, sensors, monitors, and networked appliances [1].

Industry and policy discourses about SHTs include assumptions and explicit claims that they will enable domestic energy efficiency and environmental sustainability [2]. Energy providers in Australia are promoting smart homes and SHTs as a strategy to reduce energy bills. For example, *Red Energy* lists robotic vacuums under 'energy-saving gadgets for smart homes'.[1] In addition to energy efficiency, the energy policy sector anticipates that households will use SHTs to manage their energy bills in response to smart meter-enabled 'time-of-use' electricity tariffs designed to shift the timing of electricity consumption [3]. For example, the UK government's strategy to deliver 'a more flexible energy future' wants to enable 'smart homes' by facilitating use of smart appliances and battery storage for home-generated clean energy[2] [4]. The European Union's Strategic Energy Technology Plan (EU SET) also aims 'create technologies and services for smart homes that provide smart solutions for energy consumers' [5]. While these policies do not necessarily mention robovacs specifically, they form part of an overall policy discourse which presents smart homes and their technologies as inherently more energy efficient and beneficial to the electricity grid. However, social scientists such as Wilson et al. [6] and Darby [7] have previously questioned the energy-saving claims from SHTs. Our paper sits within this emerging body of social scientific research exploring 'what happens in human-technology interaction across different scales as new gadgets are introduced', and what are the consequences for energy demand ([2], p.2).

Alongside energy management, SHTs are expected to deliver other benefits to households such as comfort, convenience and safety [8,9]. The scope of smart control is ever-expanding and now covers many aspects of everyday home life including: lighting; shading and ventilation; heating and cooling; hot water delivery; security and privacy; entertainment (audio-visual); refrigeration; cooking; laundering and other cleaning activities. In past research, we have demonstrated how

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[1] https://www.redenergy.com.au/living-energy/smart-homes/energy-saving-gadgets-for-smart-homes.

[2] On-site generation and battery storage are also commonly referred to as smart home technologies, but are arguably quite different in that they provide (rather than consume) energy.

https://doi.org/10.1016/j.erss.2018.11.019
Received 17 June 2018; Received in revised form 12 October 2018; Accepted 29 November 2018

the marketing of off-the-shelf SHTs and integrated home control systems includes energy management as one of many promoted benefits including control and empowerment, comfort and relaxation, security and peace of mind, and convenience [10]. Similarly, Darby's [7] review of literature on SHTs identified energy efficiency as a separate narrative to the lifestyle 'problems' narrative that home automation is expected to address (e.g. securing the home and its occupants). In this paper we bring these energy and lifestyle narratives together around the key domestic pursuit promoted through robovacs – cleanliness.

Importantly, as households embrace industry and policy visions of energy efficiency gains whilst simultaneously pursuing lifestyle enhancements, smart homes and their devices could *increase* energy demand. Apart from the energy consumption of SHTs themselves, researchers have raised concerns about the normalisation of new energy-demanding practices enabled by SHTs [11], encouraging more-resource intensive conventions of convenience and comfort [12], and increasing dependence on SHTs for non-essential luxuries in household life. A recent nationally representative survey of the (perceived) benefits and risks of smart homes found that prospective smart home users in the UK 'have positive perceptions of the multiple functionality of SHTs including energy management' ([6], p.79–80). A nine-month field trial conducted by the same researchers involved a range of SHTs but found little evidence for energy savings and noted the risk that SHTs 'may generate forms of energy intensification' ([13,14], p.127). In Australia, a trial of off-the-shelf SHTs similarly demonstrated that the comforts and conveniences enabled by SHTs can divert household attention from energy management [15].

The potential for new home technologies to have unintended outcomes is not new. Historical analyses of the home have shown how technologies and infrastructures intended to make home life more efficient have transformed expectations and increased resource use (and some forms of household labour) over time [16,17]. Focusing on these changing expectations, Shove draws attention to comfort, cleanliness and convenience (the 'three Cs') as constituting the 'environmental hot spots' of home consumption [18,19]. She argues that those interested in pursuing sustainability or changing patterns of consumption should focus their attention on these changing conventions, rather than on improving the efficiency associated with specific technologies or devices. For example, Jack's [20] study of cleanliness practices in Sweden illustrated how collective conventions of bodily cleanliness are often performed to meet the perceived expectations of others rather than to maintain health, and how material infrastructures such as appliance ownership contribute to resource consumption in the pursuit of this cleanliness.

In this paper, we focus on how the robovac is potentially changing the conventions of cleanliness in homes. Convenient ways to clean the home receive significant attention from the smart home industry, and are part of Microsoft founder Bill Gates' vision for 'a robot in every home' [21]. Robovacs are particularly significant because they are the most widely adopted computational robot in the world, with over 10 million in circulation [22]. They are part of a suite of emerging smart cleaning technologies including robotic mops, window cleaning robots, surface scrubbers, air purifiers and self-cleaning pet litter boxes. This paper aims to understand how visions of cleanliness and order in the smart home – promoted through cleaning devices like the robovac – could impact on household energy consumption and health outcomes.

In the following section we outline some related historical developments in conventions of cleanliness. We then draw on a content analysis of articles about smart homes, robovac marketing materials, and ethnographic research with households to explore the links between smart and clean homes. We find that robotic vacuum cleaners respond to existing tensions about how to keep busy homes clean enough, but risk raising expectations of cleanliness and order. We conclude by providing suggestions for how energy policy makers and advocates can respond to the identified risks for energy consumption and the environment.

2. Shifting conventions of cleanliness

Conventions of cleanliness have fluctuated over time, by location, religion and social class. For example, conventions of bathing and bodily cleanliness (e.g. in Ancient Rome, the Middle Ages) have been interspersed with fears that immersing the body in water can be physically or morally harmful [23]. Importantly though, these ideas have not necessarily been about health. In the 1800s, the cultural historian Jacob Burckhardt observed cleanliness to be 'indispensable to our modern notion of social perfection' ([24], p.1). In the Victorian Age, ideas of cleanliness were increasingly integrated with moral propriety and social status [25] while living *with* dirt was seen as positive and healthy in other places, such as rural America [26]. As the role of human effluent in transmission of illnesses became widely accepted, America and Europe's pursuit of public sanitation projects and cleanliness linked ideas of health together with morality, self-control, and advancement [27]. These notions of cleanliness as a *better* way to live (rather than just a healthier way) helped to convince people to participate in promoted hygiene practices [18,19], and home cleanliness acquired heightened societal importance.

In the 20th Century, households were encouraged to adopt mechanical, and eventually electrified, cleaning appliances. Diversion of domestic service workers to war efforts, and emergence of alternative work opportunities (particularly for women), increased household demand for devices to reduce the manual labour involved in home cleaning [28]. In the 1930s, the United States Government offered households loans to purchase home appliances as part of 'household modernization' efforts [29]. After the Second World War, 'servant-less' homes enabled by labour-saving devices for cooking and cleaning were promoted heavily by the popular media [28], including in magazines such as *Good Housekeeping* and *Ladies Home Journal* [30]. The domestic work involved in being a 'good housewife' was rebranded as 'scientific' or 'household engineering' [28] requiring the use of mechanical and automatic technologies.

In some cases, people needed considerable persuasion to consider adopting these devices. In Denmark, for example, 'authorities' were set up to overcome scepticism and resistance to adoption of electrical appliances such as the vacuum cleaner, and the hygiene, efficiency and technical aspects of housework appliances were promoted to housewives [31]. By the mid-1950s, most UK homes had mains electricity supply. The London Electricity Board and later, industry organisations, promoted electrical washing machines, tumble dryers and vacuum cleaners as convenient and healthy additions to the home [32]. For example, electric dishwashers were promoted as a superior way to reduce transmission of disease within the home compared to manual washing and drying.[3]

While these targeted attempts to embed health practices and labour-saving technologies into homes didn't determine exactly how they were used, they did lead to persistent understandings regarding the 'right' way to clean and how clean the home should look, smell and feel, generating long-term implications for residential energy consumption [33]. For example, understandings that washing clothes in hot water 'kills germs' still persists in some countries today – despite water temperatures in home washing machines being too low fulfil this claim and little evident health advantage [34]. Similarly, clothes dryers are often understood to be more hygienic than outdoor drying despite the disinfection capabilities of ultra-violet radiation from the sun [35].

Appealing to and cultivating consumer feelings of inadequacy in many domains of life, including cleanliness, is a tried and trusted marketing strategy [36]. Implicit or explicit notions of health are common in cleaning product marketing regardless of evidence for health benefits or otherwise, and imagery is used to communicate ideas about health and conventions of cleanliness. However, as Schwartz

[3] Jenny Webb https://www.youtube.com/watch?v=k5MjSSxy8XE.

Cowan and other social historians of technology demonstrate [16,33], marketing strategies and new technologies don't *determine* use or outcomes in households. Instead, as evident in Sarah Pink's ethnography of cleaning practices in several countries (e.g. [37–39]), there is considerable 'flex, slop and play' ([40], p.92) in how new technologies and the ideas they promote become integrated into the everyday practices of households and, consequently, what impact they have on resource consumption. This suggests the need to understand how new technologies are incorporated into the home, where they interact with a range of other occupants, devices, and other objects.

Following Schwartz Cowan's analysis of the 20th Century industrial revolution of the home [17] – the arrival of a range of smart cleaning appliances as part of the 21st Century's digital revolution of the home has the potential to further increase cleanliness expectations. In the following section we outline our methodology for investigating changing cleanliness conventions, and their associated energy and health implications, in Australian households who have adopted robotic vacuum cleaners.

3. Methodology

The research discussed in this paper was part of a three-year study of Australian households living in smart homes or using SHTs called Automating the Smart Home. As part of this project, over 250 international smart home articles published from 2000-16 in industry and consumer magazines, newspaper articles and online, were systematically analysed in NVivo qualitative data software. Articles were sourced by searching online and academic databases for the terms 'home automation' and 'smart home', including variations and derivatives (e.g. networked or connected home). Only articles explicitly discussing the use of smart and automated devices inside the home were included. The majority of articles were written in the United States, United Kingdom and Australia and many of the articles were written by industry 'insiders' or advocates who may have vested interests in promoting smart home products. The text and primary image content (if present) were coded thematically using qualitative inductive coding methods [41]. In this paper, this dataset is supplemented with quotes derived from leading robovac product websites (from 2017-18), to capture the marketing messages and promotion of these specific devices in the context of the broader smart home article analysis.

As part of the research, we also carried out a digital ethnography study [42] with 31 households who self-identified as living in smart homes and/or use SHTs such as robotic vacuum cleaners as part of their everyday lives. Methods involved in-home semi-structured interviews and participant-led 'technology tours' [43], supplemented with photography (taken by the researchers) and a short demographic questionairre. The home visits typically took around 1 ½ to 2 h. They were voice recorded and professionally transcribed for analysis. Where possible, all adult members were involved in the research, with occasional interactions and responses from children where present. Participants were recruited via technology online forums and events, as referrals from smart home industry professionals, a project website, social media, targeted online and radio media about the project, and professional and personal networks. In this paper we focus our analysis on the 11 households who had a robovac, supplemented by comments from those who talked about robovacs (but didn't have one). The interview data was analysed for themes relating to cleanliness and order, energy consumption, and household and gender dynamics.

Of the 11 automated vacuum households, nine were couples (with or without children living at home), and two were sole parents (one father, one mother). Both adults participated in five of the nine interviews and tours as couple households. All participants were aged between 35 and 54 years, and lived in or around Sydney, Canberra, Melbourne or Darwin. Three were born outside Australia – in Vietnam, China, and Ecuador. Nine households owned their home and two rented. For some, the robotic vacuum was their only smart/automated home appliance while others had additional SHTs or lived in integrated smart homes.

Our dataset was limited by the inclusion of households who mostly identified as 'early adopters' of smart home technologies, or at least more 'tech-savvy' than the 'average' household. We note that the wider diffusion of SHTs such as robotic vacuum cleaners into Australian households may raise additional or different concerns for energy consumption.

4. Findings

4.1. A technology and energy supplement, not a straightforward substitute

Robotic vacuum cleaners use much less electricity per unit of time than traditional manual equivalents, hence their classification as an 'energy-saving' appliance. Even after factoring in more frequent use, robovacs are deemed more 'energy efficient', as noted on the environmentally-minded website *TreeHugger*.[4] However, these claims assume relatively simply substitution of one device for another, rather than considering how different devices are incorporated into household practices of vacuuming. Other than one couple living in a small rented apartment, all robovac households in our research continued to use traditional vacuum cleaners for '*proper*' cleaning (Khalil). Robovacs did not necessarily reduce the frequency of manual vacuuming, but provided an additional vacuuming supplement. As Miles said, '*it doesn't replace the vacuum, but it just hoovers up those little crumbs that are annoying*'.

In addition to supplementing manual vacuuming, robovacs encouraged more frequent robotic vacuuming in several different ways. Firstly, households' attempts to overcome perceived deficiencies in the technology contributed to frequent robotic vacuuming, '*it kind of meanders around the room and it makes an effort to try to get the whole room but it's never going to get 100% of it. So I think the more often you run it the better it works*' (Oliver). Secondly, with robotic vacuums designed to be stationed in a room (not stored in a cupboard), the proximity and ease of switching on a robotic encouraged '*opportunistic*' cleaning [44] whenever untidiness was noticed. For example, Lung used the robotic vacuum in between services from a professional cleaner. He said, '*when I just see the hair [on the floor], I just press button until it goes'*. Thirdly, other households used default '*auto daily cleaning*' [45] settings as promoted by robotic vacuum marketers: '*Cleaner floors. Every day. All at the push of a button*' [46].

Supplementary electricity use associated with robotic vacuuming was particularly evident in households who had previously vacuumed infrequently or not at all. For example, before buying a robotic vacuum, Angela swept floors manually and '*never vacuumed*'. She described how using the robotic vacuum delivered '*an improvement'* on her still '*not up to scratch'* floor cleanliness. Ursula said that before buying the robotic vacuum, '*we weren't, probably cleaning as much as we would like*'. The device now cleans their floors in the living room and kitchen *'two or three times a week and does the rest of the house a couple of times a week and the kid's room once or twice a week'*. As a result, Ursula was pleased to *'have cleaner floors*'.

Despite expectations that the potential for robotic home appliances to replace manual work will drive their adoption [47], our findings build on other research demonstrating that this isn't usually the case. For example, Sung et al.'s [48] survey of over 300 users found a statistically significant increase in vacuuming frequency after robovac adoption, because most households still vacuumed manually. However, neither the energy nor household wellbeing implications of robovacs being used as supplementary or complementary cleaning devices were raised by the authors. A subsequent paper concerned with the technical

[4] https://www.treehugger.com/gadgets/is-it-greener-to-use-a-roomba-or-an-upright.html.

Fig. 1. Robotic vacuum cleaner working in a clean, clutter-free home.

aspects affecting robovac energy consumption and in-home usage patterns concluded that robovacs 'will usually never completely replace the manual vacuum cleaner, as it cleans less efficiently' ([49], p.386).

These findings and studies also reflect research conducted on other failed 'substitution' technologies, such as information and communication technologies, which were originally expected to replace some of the need for air travel in facilitating business meetings. Similar to the example of robovacs, mobility scholars have highlighted how telecommunication technologies have instead supplemented and expanded the role of international travel [50,51]. However, while earlier studies support our finding that robovacs tend to act as supplementary cleaning devices, there has been little attention to the overall energy implications. This highlights the risk that energy advocates will encourage households to adopt a robovac or another SHT in the pursuit of energy efficiency, regardless of whether the device will reduce the overall electricity demand used to clean household floors. We now explore other aspects of robovac adoption which could impact energy or wellbeing outcomes for households.

4.2. Meeting cleanliness and tidiness expectations for other people and the robot

As indicated in the previous section, householders often doubted that they were keeping their floors and homes sufficiently clean and tidy. This concern competed with other practices including work, education, raising children, and wellbeing activities such as healthy cooking and exercise. As Kelly said, '*[cleaning is] one of these things that we always feel like we should be doing more of …[cleaning] can't be so important that it overrides our other priorities, but we don't feel comfortable just being complete slobs either*.' Householders' dissatisfaction with perceived '*mess*' or '*dirt*' in their homes was not expressed as a concern for occupant health, and it is highly unlikely that the level of cleanliness in any of their homes (before or after obtaining a robovac) would be a direct risk to physical health. Instead, home messiness was linked to perceived cleanliness expectations of others – within or beyond the home. Marilyn preferred to sweep and joked that she could '*just take [her] glasses off*' but her husband thought vacuuming was necessary and, along with the kids, took responsibility for this chore. Kelly and Oliver explained their shared acceptance of mess and concerns about perceptions of others:

> 'It would be embarrassing if other people came over… [otherwise] we would probably just not get too stressed out about it, just let it get messy…' (Kelly)
> 'We'd let ourselves and each other off the hook a bit at times… when we're both busy.' (Oliver)
> 'As long as like the food areas are kind of clean I don't mind.' (Kelly)

The above exchange illustrates the difference between maintaining cleanliness in food preparation areas to minimise health risks, and the way much cleaning is performed in response to the perceived opinions of others and the social unacceptability of '*mess*' or uncleanliness [20,52]. Robovacs became part of these attempts to uphold conventions of cleanliness more easily and continuously. Some households indicated that the robovac reduced or eliminated the need to employ a human cleaner, and cited this as beneficial to reduce household expenses or privacy concerns regarding having human helpers in the home.

Meeting or failing to meet cleanliness conventions could impact householders' peace of mind and presumably wellbeing. As Miles said, the robovac's ability to regularly remove the '*crumbs*' dropped by children '*gives me sanity*'. This speaks to Martens [53] point that cleaning can provide a productive sense of control within hectic lives. However, advertising, health and education imagery featuring 'ideal' home environments is a likely contributor to understandings of what 'needs' to be controlled (e.g. floor cleanliness), and the visceral feelings householders express about minor untidiness in their homes.

Marketing of smart homes and their devices depicts a spotlessly clean ideal of domesticity, typically in open-plan (and often large) homes (see Fig. 1). Our content analysis of articles about smart homes and their technologies found only three images (from a total 166) depicting any form of manually-performed domestic activity (cooking, laundering, child caring, house cleaning, dishwashing etc.). Of these, two were cartoons and the other a photo of a robotic (and headless) device preparing food. The absence of 'real' humans performing common domestic chores in smart home and robovac imagery contributes to a sense of effortless cleanliness. Although infrequently included, any home occupants depicted (most typically young to middle-aged Caucasian women or couples) are usually enjoying leisure activities in their spotlessly clean homes. In promoting a particular visual ideal of home life, the marketing and design of these devices are likely to raise cleanliness expectations by tapping into household concerns and seeking to amplify them.

Alongside default settings for daily vacuuming, product marketing focuses heavily on addressing the issue of pet hair – which is positioned as problematic, unsightly, unclean, or dangerous. Allergies to pet hair do occur and affected households may avoid having allergenic pets or seek to reduce pet hair in the home. However, households in our study did not attribute their concerns about pet hair in the home to allergies or physical health. Instead, the robotic vacuum appealed to '*distress*' (Valerie) about pet hair contravening conventions of tidiness.

> '[Our dog] lives with us inside and she sheds a lot, so it's a source of distress for me to see the house in a mess… [I got] one of those robotic vacuum cleaners … so at least the house will not be so dirty.' (Valerie)
> 'I love [the robotic vacuum] because this is quite a big area and with the two cats… you do have to use it quite often and the amount of cat hair that it picks up it's really good, it stays on top of it.' (Kristi).

To some extent, robovacs demand a home that meets the ideal of

tidiness presented in marketing imagery – one devoid of stuff or clutter on or around the floor [54]. In this way, they could also exacerbate the concern caused by an untidy or 'dirty' floor. A few households struggled to provide an appropriate environment for the device to operate at all. Valerie gave up using the robovac because she couldn't meet its implicit demands for tidiness:

> 'At first I thought it was the best thing ever… so we'd call it "Happiness"… But then the Happiness was very short lived… I'll go to uni or something and then I ask the children please make sure that the, that Happiness is working and not stuck somewhere… I'll come back home and the house is a mess and the [vacuum cleaner] is stuck underneath it… so it was a source of distress as well.'

Two others had received the robotic vacuum as a 'hand-me-down' from friends or relatives who experienced problems using the device because their homes were not sufficiently tidy and spacious. Khalil said his brother '*couldn't use [the robotic vacuum] in his house because he had too much furniture, it was too small a place… We have quite a lot of open space so it's suitable here*'. The devices also tended to get caught on objects such as rugs, wedged in tight spaces, confused and inert in spaces with too many objects, or knock things over. Other research has reported rejection of robotic vacuums due to insufficiently large rooms [55], or as described Vaussard et al. [49], 'incompatibilities with the user's ecosystem' ([49], p.376). An early study of robotic vacuums concluded that 'fundamental changes in the structure and infrastructure of the home will need to take place to support autonomous service robots in the near future' ([44], p.129).

Some households in our study reorganised or modified their homes to suit the robotic vacuum, as found by Sung et al. [48]. Miles described some of the issues, '*it will pick up random toys from the kids. Kind of have to do a bit of cleaning up before you turn the robot on. It'll hook up on cords, and stuff like that'*. Ursula and Noel felt their home was '*cleaner*' and '*nicer*' as a result of having a robotic vacuum and they stopped employing a human cleaner. They were willing to *'make the house a bit more compatible'* with the robot in order to support its particular requirements for vacuuming:

> 'The height underneath [that cabinet] is just a little bit higher than "Flat Bob" [family's name for their robotic vacuum cleaner]… he used to get stuck under there so we put bricks under there so he can't get under there at all.' (Ursula)
> 'If we were buying a cabinet, if we buy something with a gap that size under it either bigger or smaller but just the same height, that's not good.' (Noel)
> 'I just thought about putting some beading around the edge at some point to stop Flat Bob from being able to get underneath. Just slightly more attractive than a brick.' (Ursula)

This couple's experience illustrates how robovacs can encourage households to reconsider the layout of their home and consider the needs of the robot when selecting new furniture or objects. In demanding preparation for vacuuming, decluttering, and/or particular types of maintenance, robotic vacuums can instigate new cleaning routines and room arrangements.

4.3. Automation as part of the family

Robotic vacuum cleaners were often described as more than a purely functional device. Householders indicated affection for these appliances that provided help to the family, and talked about them in ways which differed to less-autonomous appliances like dishwashers and microwaves. They commonly assigned them with genders and/or names. For example, Ken described the way their '*best friend*' handled a household problem:

> 'Dark carpet…everything shows up, crumbs and dirt and things… he kicks in when we leave for the day and does the cleaning. And the vacuum's probably our best friend, because as we leave we just turn him on, and when we come back the floor's clean'.

Signs of affection for the robotic vacuum pointed towards its involvement in '*moments of fun and trouble*' ([56], p.48) in several ways. Firstly, the robotic vacuum's sounds, appearance, movements and experiences helped animate the device. Kristi and Bill laughed together about how '*Sam*' could '*suck up a pair of her undies and jam on them… choke on them'* (Bill). Kristi who '*wouldn't call [her]self necessarily a high-tech person'* contrasted her feelings about the robovac with her microwave. When the microwave beeped she perceived it as a '*kind of nagging… I feel like it's a nag. It's like yeah alright I'm getting there*'. Whereas the robotic vacuum depended on her for help, and the '*relationship*' involved '*love*', and *'forgiveness*', '*I just love it so much I kind of forgive it. Yeah it's a different relationship… it really helps out so much that if it gets stuck I'm, I really can forgive it'*.

Being more animated than other appliances contributed to robotic vacuums being viewed as a family pet. For example, Angela would tell her children to *'get "Scuttle Bug" and clean it up'* and that '*it's kind of like a pet'*. "Scuttle Bug" was just one of the pet names used by households to refer to their robotic vacuums (see also "Flat Bob", "Happiness", "RoRo" and "Sam" in other quotes), a finding that follows other robotic vacuum research showing that householders anthropomorphise their devices [48,57]. Children were sometimes involved in proposing the name which was then used widely by household members.

Treating the robot as a pet helped make the vacuum fun and engaging to children – which in turn assisted parents in enrolling children in cleaning-related chores such as preparing the floors for the robot (picking up items which could be problems for operation), turning the robotic vacuum on, and taking care of it when it encountered difficulties (such as getting stuck in a corner). April and Ken turned looking after the robovac into a '*game*' for the children, '*when I get home, if the "RoRo" vacuum gets stuck and it's not back in his bed [charging socket], they go and find it. You know how it gets stuck, in a small space… They race to find it. It's a game*' (April). Angela, noted that '*being a single parent, I just need them to do more',* referring to engaging her children to help with the robovac.

Dautenhahn et al. [58] have previously found that households want robot assistants to fill 'butler', 'servant' or 'machine' roles, but not be 'friends'. However, the pet-like role in family life found in our study indicates a more relational role for robotic vacuums as materials in household practices, as proposed by Strengers [59]. The 'friendly' associations householders make with their robovacs reflects Nass and Yen's [60] observation that people make emotional connections with machines. Anthropomorphism of robovacs may also serve to soften tensions around the role of robovacs in gendered division of domestic labour. As in many countries [61], responsibility for domestic chores such as cleaning remains heavily skewed towards female members of Australian households [62]. In our study, robovacs were used to respond to concerns about unequal contributions to domestic labour in some homes. For example, as Noel who worked long hours as an academic described:

> 'The more [cleaning] can be kind of handled in an easy way the better – because it's potentially, you know [a source of relationship] problems… creates tension so having one less chore … I think actually it's quite a big thing in terms of minimising one's source of stress around the house.'

The technological and time efficiency aspects of automation appealed to men more than women, and they often proposed adopting a robovac to make floor cleaning easier – either for other family members or themselves. Khalil said, '*when we first moved in we just split up some chores. So I nominated for [vacuuming]… Not very long [after I bought the robotic vacuum cleaner]. It happened pretty quickly… I liked it'*. These efforts were not always positively received by the robovac proponent's partner. Khalil said his wife '*thought it was me cheating*'. Outsourcing

domestic responsibility to a robot could be seen as taking an easy way out but could also be laughed off, as feelings of affection towards robovacs and their adoption into the family helped to dispel tensions around this topic.

Our own and others research [48] showing that robotic vacuums can help switch responsibility for vacuuming to male or younger household members is an example of how robotic cleaning devices can redistribute the responsibilities of housework in the home (including adding technology maintenance work particularly for men [63]), and ensure that social expectations of cleanliness are upheld with minimal effort. However, as well as meeting existing cleanliness expectations or redistributing responsibilities within the home, robovacs can also play a role in shaping and escalating those expectations.

4.4. Growing demand for automated cleaning automation

More than half of the households from our study who did not have robovacs indicated interest in buying one but, based on reports from others (including online reviews and forums), had decided to wait for the technology to improve or come down in price. They doubted that current (affordable) models would clean effectively enough or navigate their home intelligently. Men were particularly interested in adopting automatic vacuums once the technology met their own, or other users', expectations. Kurt said he '*spent some time looking at robotic vacuums*' but:

> 'They don't think that they clean well enough on their own. That's the general consensus… that would be a labour-saving device, which is particularly why we would get it because both of us don't vacuum probably enough. But… unless you're willing to spend $1000 they don't have a brain… that will be something I'd love to see, a cheap brainy vacuum'.

Despite the reported imperfections of these devices, robovac adoption acted to further household demand for more SHTs with cleaning capabilities. Households often acquired a robovac after friends or relatives talked about them positively. Others were tempted to upgrade to more recent models with anticipated technology improvements ('*getting stuck on rugs or under furniture, it's not a perfected science yet*' (Bill)), and some households had already upgraded to a newer model. Although householders often doubted the feasibility of other automated home cleaning devices being developed, the idea was appealing. Saul said, '*I can't think of too many chores that can be automated in an actual legitimately beneficial way*' but also that '*the time that chores take to be done, [it] would be good to automate*'.

The prospect (or reality) of saving time and achieving family harmony could outweigh any concerns about embodied energy, disposal, and electricity implications of robotic vacuums. For example, Ursula and Noel were trying to minimise '*consumery*' practices (avoid unnecessary purchases), and minimise energy use in daily life, but their positive experience of having a robovac made them think about other cleaning chores for which they would ideally have a SHT. These activities included those currently done without use of an energy consuming appliance, such as window cleaning. Ursula said, '*if we're thinking open sky ideas I would be extremely happy for automated devices to do all the cleaning, if it were possible*'.

The generally positive experience reported by all but two households suggested that emerging SHTs which perform and increase home cleanliness will be embraced by them in the future. As Angela said:

> 'I think it's the beginning of a lot of this technology so it's still all very sort of clunky and I guess you know all of that sort of stuff is going to be better, and there's going to be more. Like I've got a robot vacuum cleaner which I've had for years and I love… I could see how you could set all of that up. So your house was more automated'.

These findings indicate that the introduction of a robovac can act as a catalyst for other emerging smart cleaning appliances and robotic devices that are likely to further escalate energy demand in the home. Provided that it is deemed 'useful', the robovac can act as a 'gateway' appliance that paves the way for the further automation of home cleaning, including for tasks that previously involved no or very minimal energy consumption.

5. Discussion and conclusion: is striving for cleaner homes smart?

Most published robotic vacuum cleaner research arises from efforts 'toward the goal of making domestic service robots useful, usable, and acceptable everyday tools' ([55], p.389) or improving energy efficiency of the technology (e.g. [64]). Ethnographic work from the field of Human-Computer Interaction embraces the potential for robotic '*social products*' to 'foster social relationships between people and systems' ([44], p.129). Our research with self-initiating adopters of SHTs (not recipients of robotic vacuums provided as part of a study) aligns with previous findings about the ways that robovacs can become part of household life – but raises questions about the broader impacts of such social products for household energy use, consumption and wellbeing. More broadly, household robotic vacuum cleaners provides an illustrative example of how 'technology designed to improve efficiency [could] backfire when unaccompanied by broader social and cultural change' [65].

While uptake and the ways that SHTs are integrated into household life will vary (e.g. due to economic, housing, cultural differences), the findings in this paper are likely to be relevant for other affluent countries. The robovac is particularly pertinent in this regard, given it is currently the most widely adopted robot in the world. Importantly, current demand for this device is not borne out of a one-dimensional desire to make cleaning chores quicker and easier. Households in our study sought, or responded to, the ability of robotic vacuum cleaners to deliver more frequent cleaning, as found in previous robovac research. These findings also reflect the trajectories of other home appliances (e.g. washing machines) and services (piped hot water) [18,19], which have previously contributed to increased standards of cleanliness and resource consumption in the home. More specifically, our findings warrant three important considerations for anyone interested in reducing household energy consumption and environmental impacts via SHTs such as robotic vacuum cleaners.

Firstly, while the robotic vacuum was abandoned or used infrequently in two households, most households accepted the device's deficiencies, forgiving and making up for them with additional human effort, including regularly using a manual vacuum cleaner for more thorough cleaning. This demonstrated use of robotic vacuum cleaners as supplementary and complementary vacuuming devices (instead of substitute appliances), brings into question both marketing claims and broader understandings of robotic vacuum cleaners as 'energy efficient'. While there is no agreed amount of energy that can be saved by automating the home, and estimates for different discrete devices vary, popular media articles suggest significant energy efficiency gains for householders. For example, one article claims that they can 'easily lower… utility bills by 10% to 25%' and are 'a good solution to help preserve … natural resources' [66]. As noted in the introduction, SHTs and their integration with smart grids are also widely expected by policymakers to deliver more energy efficient cities, including delivering 13 to 24% reduction in peak electricity demand [67]. Our research adds to a growing body of evidence demonstrating that reducing carbon emissions and/or peak demand from SHTs is not straightforward or guaranteed outcome (e.g. [7,11,13,14]).

Energy policy discourse around smart homes should accurately reflect the full range of possible energy outcomes from uptake of SHTs. Even if households do not engage directly with energy policy documents, the smart home industry can utilise policy claims and anticipated benefits to promote SHTs to households. One of the issues is that home technologies described as 'smart' are broadly appealing,

particularly to younger adults for a range of reasons noted earlier, such as their promise of convenience and connectivity [6]. Although the combination of home energy generation and storage technologies with smart appliances can potentially achieve energy demand reductions, in reality many advocates of SHTs have little concern for actual energy outcomes in the home. A redefinition of 'smartness' as energy efficiency might make sense [68], but not when combined with the broader lifestyle visions promoted by SHT advocates and popular media that continue to conflate smart with a host of other aspirations likely to undermine energy reductions. Therefore, energy policy makers and advocates should be wary of contributing to consumer perceptions that uptake of smart appliances will automatically translate to more energy efficient homes, and actively seek to challenge these ideas where appropriate. This is especially important to minimise the risk of households struggling with high energy bills committing their already limited financial resources to smart appliances which deliver lifestyle benefits instead of energy savings. The desired energy efficiency and management outcomes (and climate change mitigation) are more likely to be achieved if both optimistic technical possibilities and the ambiguities and risks concerning adoption of smart home appliances are given due consideration in policy, planning and research.

Secondly, there is considerable risk that SHTs will promote higher expectations of cleanliness (and in turn, additional energy consumption and other environmental impacts). Ratcheting these expectations (and those of comfort and convenience) could have significant impacts on household consumption [18,19]. Historical shifts in conventions of social normality in inconspicuous aspects of household life have accelerated consumption of resources [69] and robotic cleaning appliances are a potential new front of environmentally-relevant consumption. The smart home industry is not the first, nor will it be the last, to market their products as lifestyle improvements via appeals to household understandings of adequate cleanliness and order in the home. As Shove [70] explains, policymakers with sustainability concerns should 'consider the meanings and levels of service and the types of consumption and demand that efficiency policies support and perpetuate' (p.1). SHT-enabled conveniences appeal to households [71] and expansion of robotic cleaning appliances to other areas of the home is likely. As luxury or novelty appliances can rapidly become expected and normal and parts of home life [72], there appears to be potential for robotic cleaning devices to become a significant new front of household consumption. The propensity for robotic vacuums to enter the home as gifts could contribute to such an outcome [48].

In the event that both manual *and* a robotic vacuuming becomes the household norm, the environmental impacts of materials, production and disposal of floor cleaning devices will be significant [73]. One study identified that due to lack of end-of-life design thinking, even in the best case scenario only 47% of robotic vacuum cleaner materials would be recyclable [74]. The increasing frequency at which vacuum cleaners are discarded and replaced will contribute to this waste [75]. Beyond floor cleaning, a trajectory towards greater cleanliness of homes and their occupants has wider environmental considerations including increased energy and water use and contamination of water ways with non-biodegradable plastics, wipes and chemicals which reduce the effectiveness of sewerage systems and impact aquatic life.

Third, our findings suggest that robotic vacuums could act as a 'gateway' appliance to the adoption of other automated home cleaning appliances introduced to the SHT market. Appliances such as robotic mops and window cleaners could also increase mopping and window cleaning frequency, similar to the ways in which more accessible washing machines can lead to more frequent clothes washing [20]. The availability of a wider range of automated appliances to perform cleaning chores previously carried out without using electricity would likely result in a range of supplementary household electricity demands extending beyond the example of robotic vacuuming. It's possible that these devices may pave the way for an entire robotic workforce in the home, combined with elevated expectations of cleanliness, thereby substantially increasing the energy demand of 'smart homes'.

How then, can the energy sector respond? In past research we have found considerable resistance from energy policy makers and utility providers to intervene in practices implicitly or explicitly promoted as having health benefits, regardless of inconsistencies and shifts in health authority recommendations (e.g. using air conditioning for infant health) [76]. However, questioning any assumed health gains from SHTs such as robovacs could certainly be one possible response.

In the 19th and early 20th Century, hygiene and sanitation developments improved public health, but emerging evidence calls into question the logic of pursuing higher levels of household cleanliness. A recent assessment of disease transmission in the home indicated that inadequate food storage, food handling and hand washing practices contribute [77], but there is little likelihood that greater general cleanliness and tidiness of already clean homes will improve physical health. Indeed, counter-productive outcomes are now being proposed. For example, the 'hygiene hypothesis' [78] links reduced exposure to microbes to autoimmune conditions. Rapid change in cleanliness practices in Western lifestyles has contributed to dramatic shifts in the microbial flora associated with human bodies [79]. The 'microbiome' is now thought to be involved in many health conditions with immune mechanisms – including asthma, inflammatory bowel disease, allergies, diabetes and obesity [80]. Exposure to dogs [81] and farms [82] reduces childrens' risk of asthma and allergies. The beneficial impacts of microbial diversity are an increasing focus of medical research (e.g. [83]) and treatments aimed at increasing microbial diversity in the gut, such as faecal transplants, are delivering promising results [84]. Recent research has linked lack of exposure to microbial diversity to childhood leukaemia [85]. These developments suggest that eliminating pet hair on the floor – a central target for robovac marketers and users – is an aesthetic pursuit unlikely to deliver health gains.

Robotic vacuums are also promoted as benefiting health by reducing dust and allergens.[5] It is unclear to what extent this claim is realised as Australian research suggests even vacuum cleaners with High-Efficiency Particulate Arrestance (HEPA) filters do not substantially reduce allergen exposure and can increase exposure by stirring dust up into the air where it is more likely to be inhaled [86]. Managing dust in the home is likely to benefit asthma-affected households, however supplementary 'deep cleaning' with a manual vacuum can be a response to perceptions that robovacs are insufficient to remove dust and its allergens from carpet [48].

Taking into account the two perspectives above, it may be fruitful to encourage and validate lower standards of cleanliness as suggested by past research concerned with the impact of housework on household stresses and relationships – at least in households without dust allergies [61]. This could be done through engagement between health and energy sectors to understand both energy and broader health implications of escalating conventions of cleanliness. While meeting expectations of home cleanliness using smart devices may deliver short-term feelings of wellbeing and relieve family stresses about distribution of labour in the home, discouraging further upward shifts in cleanliness expectations could bring more genuine and sustained wellbeing benefits to families, reducing feelings of inadequacy and frustration about cleanliness. Rather than presenting any genuine risk to household health, lower standards of home cleanliness could relieve household stresses and free up time for exercise, healthy cooking and social interaction – activities with far more certain health benefits than pursuing often unattainable conventions of home cleanliness.

When integrating SHTs into energy policy, Darby's [87] suggestion that instead of focusing on '*savings*' that '*often turn out to be steps taken down an upward-moving escalator*', thinking '*in terms of transformation to a low-fuel, low-carbon way of life*' ([87], p.502) warrants consideration. While those working in or for the energy sector may not feel

[5] http://www.irobot.com/For-the-Home/Vacuuming/Roomba.aspx.

comfortable to directly advocate new ways of life, they can certainly lobby, regulate and work with those companies and businesses that do. For example, easily attainable and energy efficient ideas of cleanliness could be embedded into robotic device design (e.g. through weekly or fortnightly cleaning default settings), and reflected in ecodesign guidelines. Beyond cleaning, there is a need to reconfigure visions of the smart home and SHTs towards more energy efficient and 'desirable' environmentally sustainable ways of life [88]. Policymakers and the smart home industry could also readily address the embodied energy and end of life implications of widespread uptake of a range of new household cleaning devices which may be readily discarded or replaced with newer models.

In conclusion, the promotion of SHTs draws on appealing, but inherently energy-intensive, ideas of cleanliness and wellbeing, whilst simultaneously proposing these devices as energy efficiency improvements. This paper has explored how these ambitions can mirror past outcomes for technological developments, such as ratcheting expectations that exacerbate householder anxiety about cleanliness, and increasing the energy consumption and environmental impacts arising from domestic activities [18,19]. Additionally, and reflecting research in mobilities studies and elsewhere, our study shows that SHTs may supplement rather than substitute for 'manual' household appliances. Furthermore, given the prevalence of robovacs in households around the world, we highlight the significance of this particular device in potentially acting as a gateway for the proliferation of other SHTs in homes. Seeking to intervene in the role of SHTs like the robovac in raising cleanliness expectations and energy demand in homes is a crucial role for energy policy makers and advocates if smart homes and their technologies are expected to realise their ambitions of reducing household greenhouse gas emissions.

Funding

This research was supported under the Australian Research Council's Discovery Early Career Re-searchers Award funding scheme (project number DE150100278), awarded to Yolande Strengers.

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