Fridge 2050

The future of large domestic appliances

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Contents

1 Introduction

This report reviews the current development in industry and academia of Large Domestic Appliances (LDAs). The review attempts to identify current and future capabilities and features that are likely to be utilised in LDAs. The five most common key LDA are evaluated as part of this report the fridge, freezers, cooking hobs, cooking oven, washing machine and tumble dryer [1]. The report primarily focuses on fridges and freezers, which are the most frequently found appliance in homes (sometimes with more than one per home). According to 2019 data on appliances in the UK appliance ownership [2] there was 37.65 million cold appliances (fridges, freezers or combined units), 34.86 million electric cooking hobs or ovens, 31.13 million washing machines, and 11.42 million tumble dryers. The report only covers domestic appliances and not commercial versions of these appliances. The main country of focus is the technologies and developments relevant to the UK or European market. This report provides an overview of many topics; for more details on specific topics readers should see the references provided.

1.1 Methodology

This report is a literature review based on identified sources of information. Databases of academic research papers (Science Direct, Web of Science and Google scholar), patents (Lens.org and Espacenet), and industry market reports (Statista), government reports, and manufacturers websites were searched for relevant information. Authors focused on sources published mostly in the last 10 years. Key search terms related to each appliance and variations of the name (such as fridge, refrigerator and refrigeration) were used with 'domestic', 'household' or 'home' added to focus research on only domestic appliances. It should be noted that this report does not attempt to cite all relevant literature which numbers in the tens of thousands; it aims to provide a summary of key developments and research which is currently coming to market or utilised in future products.

2 Key challenges for LDAs

From reviewing research, reports and patents on LDAs, there were several challenges and trends observed. These apply to multiple LDAs and have been initially discussed under environmental or societal challenges in this section. Challenges specific to each appliance are discussed in more detail in later sections.

2.1 Societal challenges

2.1.1 Greater connectivity

Since internet access became common in every home, there has been research into smart Internet of Things (IoT) appliances. Although the capability has been around for a while, it is only recently that consumer demand is catching up as connected appliances become more affordable and develop more useful functionality. The affordability of smart appliances has been driven by lower cost electronic components (sensors, processors, etc.) and reduced manufacturing costs. During the last ten years there has been a range of new appliances which can be connected to and controlled from our phones. More recent trends are for appliances that actively make decisions and learn using AI and machine learning. Examples include voice-activated smart fridge that can provide information on fridge contents and suggest meals to cook [1] [2] or notify you when food is going off [5] [6], robot arms that can cook a meal for you [7], and washing machines which can record clothes worn and washed [8]. Many of these capabilities will help automate our everyday life, but it is important to be aware of the security of these systems and who has access to the data collected. We may be happy for our appliance to tell us how frequently we wash clothing but not for it to tell fashion retailers. Other improvements from connected appliances are discussed in other parts of this section.

This connectivity and extensive data is likely to result in collaborations between LDA manufacturers and supermarkets or food delivery companies. An empty fridge will become an opportune time to send you an advert for a takeaway or a supermarket delivery service.

2.1.2 Ageing population

With increased life expectancy and lower birth rates, the UK is experiencing a shift to a more elderly population with a growth in physical or mental disables managed at home. The ability to remotely control or monitor appliances has proved useful for elderly or disabled users with good acceptance of these technologies [9]. Studies of cooking habits have highlighted that complete automation of process are likely to cause confusion and be intrusive, resulting in lower uptake [10]. Instead, technology should focus on assisting everyday activities rather than taking over. Examples include ovens that recognise food to set the right temperature automatically, fridges that help identify where food is [11], or appliances that turn on/off with hand gestures [9]. Less intrusive home monitoring can occur by monitoring smart appliances to tell when and how often they are used [12]–[15]. This type of monitoring could be more frequent in future LDAs as it has proved to be easier to use than body-worn sensors and could be used to monitor a patient's food intake, cooking habits or daily movements in the future.

2.1.3 Changing diet and eating habits

To maintain a sustainable and healthy diet, we will have to shift to a plant-based diet with less meat and dairy [16]. This will impact the way we store and cook food, and it may be that we look to grow food in our home to ensure fresh supplies. Alternatively, sustainable protein sources might be grown in a bioreactor or insect colonies inside our home [17]. Our fridges may store food and keep it alive; an extreme example of this is a patent for a fridge that keeps fish alive to ensure they are fresh [18]. A more likely example is hydroponics plant growers built into the fridge.

A bigger change is likely to come as people order food kits, eat takeaway food, or go out to eat more frequently [19], all habits that has increased in the last 20 years [86]. This could result in less demand for cooking or refrigeration appliances or smaller and adjustable sizing to give more spaces at home and create appliances that can change for our lifestyle.

Technology to keep food fresher in fridges is discussed further in section 4.5.

2.1.4 Changing living spaces

Generally, over the last 50 years, our living space per person has increased; however, within densely populated cities, high land cost has led to smaller living spaces [18] [19]. This leads to a need for smaller appliances completing more functions or shared appliances. Studies have highlighted that there can be emissions and resource reductions by using shared laundry facilities [22]. There has been a number of fridge concepts designed for shared living spaces [23]. Modular designs have also been presented by Samsung for small stackable fridges [24]; these fridges could allow people to increase their fridge size with household size.

2.2 Environmental challenges

2.2.1 Changing energy supply

The use phase of appliances is where the greatest environmental impact occurs; switching to cleaner energy sources is the best method of reducing the environmental impact of LDAs [25]. However, renewable energy sources such as solar or wind provide inconsistent power contributions because of their dependence on the weather, creating times with lots or little power production. There is a need for appliances to respond to the changing power provided and reduce their power demand during peak times (peak shaving). There has been lots of research on utilising smart appliances and smart meters to integrate this function into LDAs. Research modelling multiple fridges in Ireland has shown that peak power demand on the grid can be reduced [26] [27]. More recent studies in the Netherlands used washing and drying appliances; participants were incentivised to programme appliances to come on during low electricity demand times [25] [26], reducing peak load on the grid. Appliances could be designed to adjust automatically to reduce power using smart meter data.

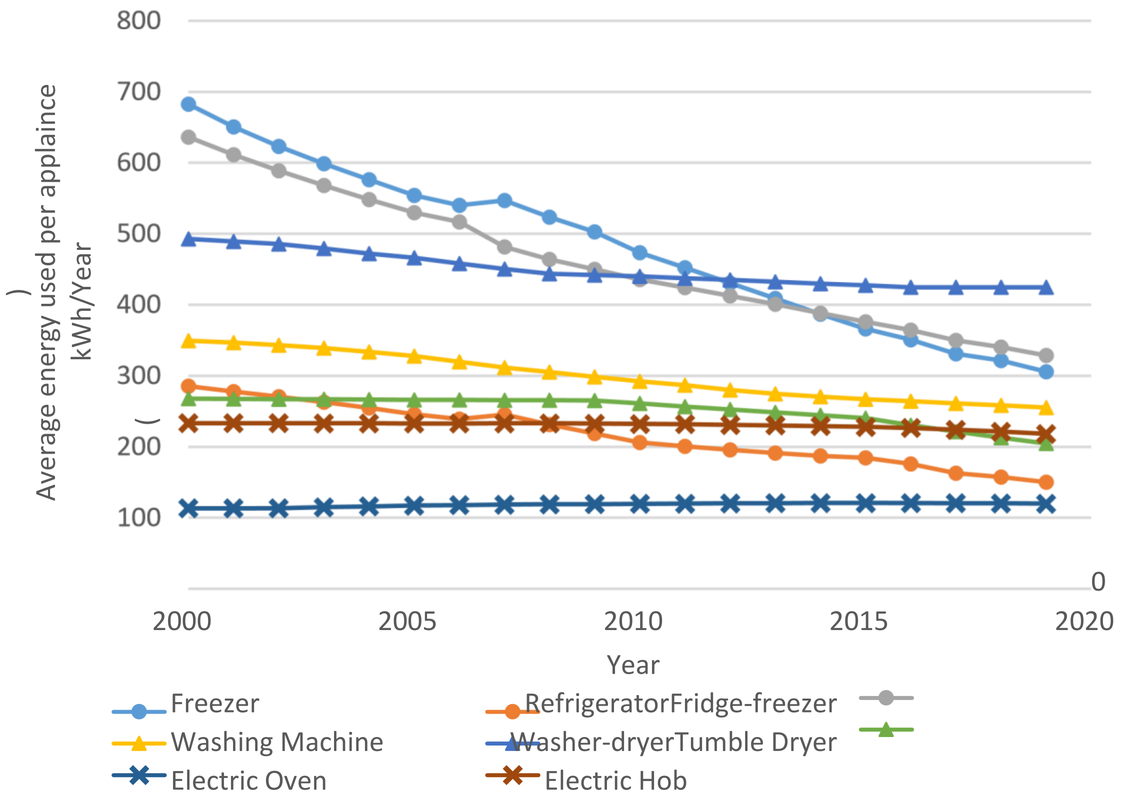

Fig. 1 – Graph of average electrical use for each LDA per year in kWh. These values are from total energy use divided by number of appliance, data taken from [2].

However, currently, there is little infrastructure or incentive in place to encourage or allow this process to happen.

2.2.2 Reducing energy use

Energy labelling for domestic appliances had been useful for increasing demand for efficient appliances [30]; this and more technology improvements have led to large reductions in energy use of LDAs. Fig. 1 shows data for the LDAs considered in this report from 2000 to 2019; it should be noted that this is total energy use, so it can also be reduced by less frequent use of an appliance. Gas use in appliances is not shown. The greatest efficiency gains have been seen for fridge/freezer appliances, which have fallen around 50% in the last 20 years. Washing machines and dryers have seen smaller reductions in energy use of 20%, probably due to heat pumps and lower water temperatures used. Cooking appliances have not reduced energy and increased for ovens; this is likely due to increase demands pre-heating speed which offset any efficiency gains. The technologies driving greater efficiency are discussed in more detail in later sections. One method to reduce energy is appliances sharing heat; for example, waste heat from fridge/freezers or ovens could heat water for clothes washing or showering. New thermal storage solutions are coming to market, which could store heat and share it between appliances or heat homes.

As our climate heats up refrigerators will need more energy to run as higher condensers temperatures will be needed to remove heat effectively. There is also likely to be an increase in air conditioning units contributing to the total energy used by appliances in the UK and reducing efficiency gains from other appliances.

2.2.3 Transition to circular economy

A circular economy (CE) aims to create a closed-loop system for sustainable businesses and production. Four key practices of CE include reduce, recycle, reuse and remanufacture (4Rs). Studies noted that currently, most appliance manufacturers do not pursue all 4R practices [31] and mainly focus on reduction and recycling, not reuse and remanufacture [32].

Reduction in energy and water use is a common theme across all new LDAs. The technologies driving this are discussed further in later sections. There is less work investigating the reduction of material use in designs, but this can be reduced by extending the use of an appliance, so fewer are made. Currently, LDAs have a relatively long life span, around 12.5 years [33]; the size and cost of a new LDA often lead to longer use cycles than other appliances. Repair projects, such as Restart Project [34], aim to extend the life of appliances, but these tend to focus on smaller appliances that are disposed of more frequently. With new right to repair laws, there could be a growing industry for the repair of LDAs. However, many consumers may see their appliance as obsolete and dispose of it rather than repairing it [35]. With new smart technology or cheaper costs, we could see appliances replaced more frequently as consumers try to get the latest features, creating more waste. Many appliances are sold on second hand to be reused, especially if newer [35]. Reuse of low-efficiency old appliances (grading C or D) can currently be detrimental, and replacing with an efficient model (A or above) offsets the resource used to make it [36].

Recycling appliances has been investigated in lots of studies [32]. Recycling will become more complex and expensive as the electronics embedded in appliances advance and contain more components. Recycling fridges or freezers is an area of major concern because of the removal and disposal of polluting refrigerants found in the vapour compression system and the insulation (see section 4.1.2.). Specialised recycling plants for processing fridges often use sealed clean rooms to trap gasses [24]. These facilities could be needed for other appliances like new tumble dryers where refrigerant gases are used in heat pumps. The utilisation of recycled material in new products is a vital way to make LDAs sustainable; manufacturers such as Whirlpool are starting to use recycled plastics in their new products [37], but there is still a need to use more recycled material in designs.

One likely trend to be seen in the future is more servitisation business models where appliances are rented to consumers or a pay-by-use system. Norsk Ombruk [38] and Bundles are companies operating in Europe that rent LDAs to customers on a per-use or per-month contract with servicing and maintenance [31]; this allows them to maintain appliances for longer and find new users for older appliances which would be thrown away. With connected smart appliances, manufactures could monitor the state of appliances in real-time. This information can be used to design better products or target repair services as and when they might be needed to reduce failures. Gorenje manufactures washing machines and rents them to commercial clients. They are starting to integrate IoT sensors into their appliances to feedback information to help improve and maintain them for longer [39]. This shift can be beneficial to companies and the environment but needs to be widely taken up to be effective [33].

Remanufacturing aims to return used products to their original condition or even an upgraded version of the original (defined in BS 8887-2:2009 [40]). Remanufacturing can create a new product using less energy and resources [41] and sold at a lower price; the greatest environmental benefit is when products are also upgraded to improve efficiency when remanufactured [42]. Currently, remanufacturing in the UK is focused primarily on automotive, aerospace, heavy-duty off-road and IT products, but could also be utilised for LDAs. Remanufacturing combined with leasing of products can prevent sale of shorter life cheap washing machines and enable lower-income consumers to buy more expensive premium products [43]. However, customers often view remanufacturing as refurbished or repaired appliances (which they are not), lowering demand; careful promotion and wording can help promote these products as sustainable alternatives [44] [45]

Remanufacturing is predominately carried out by smaller SMEs, not the original manufacturer; this can create conflicts due to IP and branding. IP legal rulings have previously favoured remanufacturers, but it is not always clear what a remanufacturer can do to other companies product without compromising existing patents or copyright [46]. Authorising third parties to remanufacture can be beneficial [47] but does mean less feedback to the original manufacturer on how to improve designs [48].

The US and China have made more efforts to support remanufacturing with more standards and incentives [49]. In 2014 government-backed reports highlighted remanufacturing as a key industry to improve UK manufacturing [50], [51]. Recommendations included improving customer awareness of remanufactured products, providing tax breaks and reviewing regulations that might prevent remanufacturing.

2.2.4 Net-Zero

The UK government is currently committed to net-zero by 2050, meaning a total of zero carbon dioxide emissions either by removal or reduction of emissions. The previous three parts of section 2.2 show key areas which need to be addressed to achieve net-zero; further considerations are also discussed here.

New technology is a key enabler of net-zero; increasing efficiency ensures that despite an increasing number of appliances power production does not increase and become harder to decarbonise [52]. As noted by a recent report by AMDEA (Association of Manufacturers of Domestic Appliances), there has been significant policy and incentives for insulating and home heating efficiency, but less policies for promoting efficient LDAs [53]. More policies are needed to encourage trade in of lower efficiency old appliances (greater than 20 years old) and ensure that more expensive energy-efficient models are accessible to a wider audience. This would help maximise the benefits of newer efficient models to reduce energy use. However, old appliances should be remanufactured or parts reused where possible to reduce the impact of disposal and energy needed for new appliances.

As noted in the Committee on Climate Change 2019 report on achieving net-zero, it is important to consider all aspects of carbon dioxide production and ensure we are not just shifting it to other countries [52]. For LDAs, that includes manufacturing, transportation and disposal. For ships and heavy goods vehicles (HGVs) transportation, hydrogen-power is likely to be needed to replace polluting fuels. Manufacturing processes need to be more energy-efficient and powered by renewable electrical sources or stored hydrogen. Whirlpool recently committed to net-zero emission in manufacturing plants and operations by 2030 [43]. Other societal changes will be needed, such as shifts in our diet to less meat and dairy (see section 2.1.3) or purchasing less new clothing; our appliances need to change to help us address and live with these changes.

The ideal way to help the environment would be LDAs which require no power to run and can be made with low energy use. Examples of these have been made for developing countries, such as hand-powered washing machines [54] or solar-powered fridges [55]. However, in the UK our appliances are unlikely to ever require no energy consumption, especially as they become more connected, have greater automation and we demand faster operation.

3 Fridges/freezers

This section evaluates the recent research and developments for fridges and freezers and highlights possible future technologies and features. The design of fridges and freezers has changed since the first commercial fridge in the early 1900s [56]; however, much of the initial design remains, including an insulated structure, a large front door and a vapour compression cycle (VCC) to remove heat.

3.1 Vapour compression cycle (VCC)

The VCC consists of a compressor, condenser heat exchanger, expansion valve, evaporator heat exchanger and a refrigerant which is moved around the system. The efficiency of fridges and freezers has increased over the last ten years [57] due primarily to improvements in the VCC, where most power is utilised.

3.1.1 Compressors

This is one of the most complex refrigeration system parts and is responsible for the largest power consumption. Several different compressor types exist currently; the type used varies depending on the cooling required in a system. Reciprocating compressors are most frequently used for domestic refrigerators due to their low size and processing capacity. Fig. 2 shows a diagram of the different types of compressors, the key types used in domestic refrigeration are highlighted in red. Reliability and efficiency are the key requirements for domestic refrigerators. Typically all domestic refrigeration compressors are welded hermetic sealed with the motor and compressor to avoid any refrigerant leaks which would reduce the reliability.

Single-acting reciprocating compressors which use a piston and crankshaft are the most common type utilised because they can be designed for small capacity intermittent operations [58]. Alternatives include linear compressors (also classified as reciprocating); they drive the piston using a linear motion instead of a rotary motor and crank. Examples include Sunpower's linear compressor with a moving magnet linear motor, used since 2002 by LG [6]. Linear compressors have the potential to allow a more efficient operation, a wider range of refrigerants and better reliability than crank driven compressors, due to being run oil-free and with fewer moving parts [59], [60]. However, this benefit has yet to be fully realised, and linear compressors are currently more expensive to manufacture due to the materials needed [6]. The other type of compressor commonly used is the rotary vane compressor which can offer higher efficiency and smaller size [58], [61].

Both reciprocating and rotary compressors mentioned above are operated intermittently; transitioning from off to on uses lots of power, and alternative designs for continuous operation have been explored [56]. Compressors are being designed with electronic inverters to create variable speeds rather than turning off and on; this is more commonly used in larger applications but can reduce energy and noise in domestic compressors as well. Electronic integration within compressors is increasing for better control, but could also allow remote monitoring and optimisation of domestic compressor performance in the future.

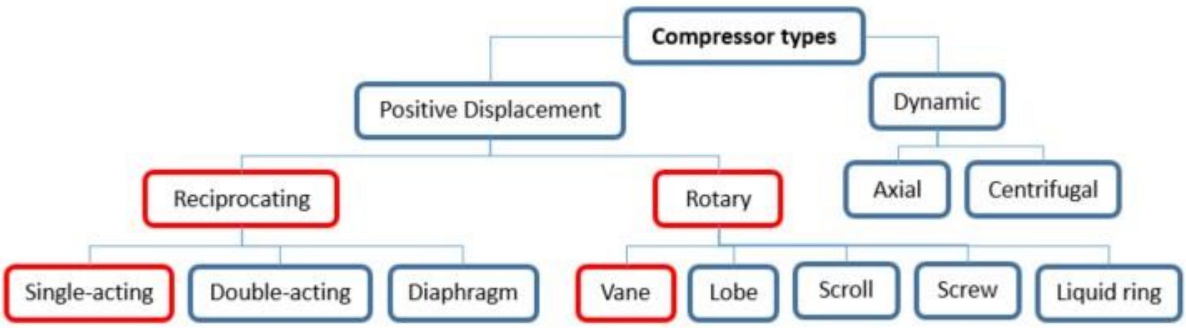

Fig. 2 – *Diagram showing different types of compressors (replicated from* [58]*), red shows compressors used in domestic refrigeration*

Some larger combined fridge designs utilise a two-stage cycle where two smaller compressors and evaporators are used (one set cooling each fridge and freezer section) [62]. However, this does increase the initial cost of the fridge.

One type of compression not noted in Fig. 2. is electrochemical compression (EC). It uses a proton exchange membrane (PEM) to force ionised gas to one side of the membrane by applying an electrical current across the membrane. This method has been used extensively for hydrogen fuel storage and fuel cells but has been proven viable for ammonia and carbon dioxide compression [63]. EC could be more efficient than current compressors with no lubrication, low noise and no moving parts; however, significant further developments are needed to improve durability, reliability and robustness [64].

3.1.2 Lubrication

Lubrication is used in compressors to reduce frictional losses and wear. However, the interaction between the refrigerant and lubricant can reduce heat transfer and system efficiency. Nanoparticles added to lubricants (nanolubricants) have been effective at increasing the heat transfer and reducing losses [65], though pressure losses do increase. Pipes, tubing and other components are all designed to enable the lubrication to return to the compressor. Removing the need for lubrication with oilfree compressors can enable more efficient component designs and boost heat transfer [66]. Developments and research at Embraco have led to the first oil-free linear compressor for domestic refrigeration (Wisemotion compressor), which appears to use solid lubricant to prevent wear on parts [67]; Embraco claim it can reduce energy use by 20% and running noise. Oil-free and nanolubricants are likely to be utilised further in future refrigeration systems.

3.1.3 Refrigerant fluid

Since the Montreal Protocol in 1987, there has been a drive to improve polluting refrigerants starting with chlorofluorocarbon (CFC), and more recently hydrochlorofluorocarbon (HCFC), hydrofluorocarbons (HFCs) and hydrofluoroolefins (HFOs) due to the global warming and ozone depletion caused by these refrigerants. The current favoured long-term replacements are natural refrigerants, Hydrocarbons (HC) such as propane (R290), isobutane (R600a), carbon dioxide (R744), ammonia (R717) or mixtures containing these [68]. Isobutane (R600a) has been the predominant refrigerant used in domestic refrigeration. Generally, HC show good compatibility with current refrigeration systems and parts, though more studies may be needed to test the long term wear on components of using HC [69] and many still have global warming potential. Due to the flammability of HC, only small amounts can be used (with limits of 150g in the EU [62]). There is not much of a risk in domestic fridge/freezers (and air conditioners), which use little of the gas, but is more of a concern in large industrial cooling applications [70]. Nanoparticles are also being tested with different refrigeration fluids to create nanorefrigerant, which have shown improved heat transfer performance in tests [65].

There is still a large quantity of CFCs and HCFCs in use in old appliances. A report from the environmental investigation agency highlighted policy action to help improve recovery of existing CFC and HCFC, and ways to discourage future use of them [68]; many of these are in place in the UK and EU already, but not in developing countries.

3.1.4 Evaporator and condenser

Condensers and evaporators essentially act as heat exchangers to either remove or add heat from the environment to the refrigerant in the VCC. Condensers dissipate heat to the surrounding environment, and are located either on the sides or back of the refrigerator. The higher the temperature of the environment, the higher the condenser temperature has to be and the lower the efficiency. It is, therefore, important that there is sufficient space for air to circulate around the condenser [56]. Some studies have tested cooling the condenser with tap water to increase heat removal and lower the condenser temperature [71], [72]. This does show energy efficiency improvements and could be integrated with hot water heating for further savings; however, it would require a radical redesign of buildings, homes and domestic fridge’s to implement.

Most research related to evaporators aims to optimise the performance of the heat exchanger by maximising airflow, plate spacing or tube layout [73]. Frost on the evaporator, caused by the buildup of moisture, leads to a loss in performance. Many fridges have periodic defrost of the evaporator with heaters to prevent front buildup [56]. Defrosting with a heater uses power and requires subsequent cooling; ideally, heaters should be placed on the evaporator where icing occurs to speed up defrosting but this also interferes with cooling [74]. One patent identified created metal strips that flexed when heated to help dislodge ice and defrost faster [75]. Other defrosting methods identified include using a bypass system with heat from the condenser stored in a Phase Change Material (PCM) [76], though this is less reliable and still requires electric heaters.

Two evaporators can be used with one in a fridge compartment and one in the freezer, to allow greater cooling control. Arrangements used include two evaporators in series, parallel or a bypass arrangement [62]. Two evaporators can be found in a number of existing fridge/freezers to provide better temperature control in each section, but the increased number of parts can lead to lower reliability.

Modelling and experiments with PCM on the compressor and evaporator demonstrate possible reductions in energy use due to lower condenser and warmer evaporation temperatures [77] [78], although longer-term tests are needed to confirm this. More energy is required when starting the VCC to cool or heat the PCM, and it adds to the material cost and weight while reducing available space in the fridge.

3.2 Alternative to VCC refrigeration

Due to low cost, efficiency and reliability, VCC is still the dominant refrigeration technology. Alternatives to VCC refrigeration are referred to as Not-in-kind (NIK) technologies; Fig 3 outlines common available NIK technologies. Many are demonstrated only in lab studies and not commercially utilised [79]. The key technologies which could be seen in domestic refrigeration systems in the future are shown in red boxes in Fig 3, including magnetocaloric, thermoelectric, elastocaloric, barocaloic, thermoacoustic, absorption and adsorption. These technologies were commonly identified in previous reviews of research papers [79]–[81] and patents [82] of NIK technologies. Evaporative cooling fridges using water evaporation were proposed in one concept design [83]; however, evaporative cooling cannot achieve the low temperatures and cooling capacity needed for effective refrigeration and freezing without being combined with a VCC. Evaporative air conditioners are available commercially but with low cooling capacity.

3.2.1 Solid-state cooling

Solid-state cooling is an area of refrigeration that utilises solid material as the refrigerant to transfer heat [79]. The application of magnetic force, stress, pressure or electric current causes the materials to either give off or take in heat [84].

Magnetocaloric cooling using an active magnetic regenerator is the most advanced solid-state method with significant recent research. High efficiencies with small sizes similar to VCC have been achieved, and wide temperature differences (between hot and cold sides). However, the technology is expensive due to a reliance on magnets and

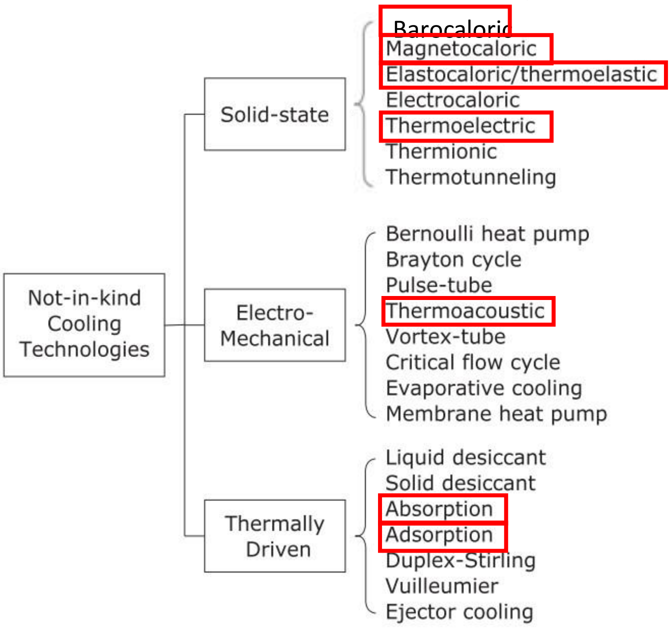

***Fig. 3** – Classification of NIK cooling technologies, adapted from* [82].

rare earth elements such as Gadolinium [81], [84]. CoolTech and Camfridge have demonstrated prototype refrigerators using magnetocaloric cooling [85].

Thermoelectric cooling devices are another well-researched solid-state cooling method. Current applied to two different junctions of materials creates a temperature difference (Peltier effect) used to remove heat [79]. There are no moving parts, improving reliability and reducing maintenance, but low cooling capacity and temperature differences hold it back currently [86]. Current and future uses are likely to be in smaller localised cooling appliances. It could be used to cool smaller food containers which people have instead of a larger fridge.

The elastocaloric effect occurs due to stress-induced elongation, while the barocaloric effect occurs as a thermal response to hydro-static pressure [84]. Both are more recent discoveries and have yet to be fully developed, with both having reliability problems, though they hold significant potential.

3.2.2 Thermoacoustic

Thermoacoustic refrigeration uses high amplitude sound waves in a pressurised gas to generate a temperature gradient [62]. Previously it has shown potential and was used in 2004 to make an ice cream freezer [87]. However, efficiency is still relatively low and long term reliability is unknown.

3.2.3 Absorption and Adsorption

Absorption and adsorption cooling operate the same as VCC, but thermal energy is the principal driver of the cycle instead of mechanical work. Therefore, a generator/absorber pair or generator/adsorber pair and a mechanical pump drive the working fluid rather than a mechanical compressor [81]. The main benefits are lower noise level, no HCFC or CFC refrigerants, and it can be powered by heat or electricity sources; however, currently, they have lower efficiency and cooling capacity than VCC [62]. There are examples of small absorption refrigerators in use around the world, though they are far less common than VCC. The ability to interface with heat sources and electricity can make absorption refrigerators useful in hot rural climates [88]; examples include the ISAAC solar ice maker [89].

3.3 Insulation

Currently, most fridge/freezers use polyurethane foam (PU) insulation panels, though some have begun to utilise vacuum insulation panels (VIPs). VIP insulation uses a core of porous material (such as PU or fibreglass materials) within a vacuumsealed packet. The evacuation of air greatly increases the insulation property leading to thinner panels and more storage space. Three problems preventing the current uptake of these panels are 1) uncertainty over the lifetime of the VIPs, 2) uncertainty over supply of VIPs if their demand ramps up, and 3) the high cost, which can be five times higher per unit area than PU [90]–[92]. Over the life of a refrigerator both VIP and PU insulation will degrade; electricity consumption can increase by 15% primarily within the first year of a fridges life due to aging [93]. This degradation is not recorded or accounted for in energy policies [94].

***Fig. 4 –** Bio-robot zero energy fridge concept by Yuriy Dmitriev, image from* [96].

One extreme way to improve insulation is to use an underground fridge which are made from a buried container, creating a walk in larder which can be cooled [95]. A consistent soil temperature of 10-15°C means less cooling is required in the summer.

3.3.1 Bio-Robot Fridge concept

The Bio-Robot Fridge was a widely publicised concept fridge that was designed by Yuriy Dmitriev in 2010, see Fig. 4. It suggested using gel to surround the food, hold it and cool it down without power [96]–[98]. Although no suitable material exists for this purpose it proposes an interesting idea that food could be submerged in a liquid or insulating medium to help cool it faster and keep it cold.

3.4 Fire safety

The most recent and comprehensive evaluation of fire safety in UK domestic fridges/freezers was done by Beasley et al. [99], [100], using data from the London Fire Brigade. It identified several electrical faults that initially caused fridge fires but noted the presence of flammable material enabled these fires to grow and cause greater harm. Three key improvements suggested were, 1) avoid plastic components (such as the backing plate and plastic tray), 2) keep ignition sources in metal boxes, and 3) limit the use of combustible foam insulation (such as PU) [99], [100]. The location and quantity of other flammable materials such as the backing plate or insulation may need to be evaluated further in future designs using HC refrigerants.

3.5 Food waste

Food waste is a significant problem all over the world. Research has shown that most consumers have their fridges at too high a temperature to store food correctly, with an average of 7°C when they need to be 4°C (5°C is the recommended temperature in the UK). A 2014 study showed that lowering fridges to the correct temperature would increase carbon dioxide from power required but this would be offset by the carbon dioxide from the food saved [101]. Many fridges lack the ability to provide accurate temperature to consumers [57]. Only a few fridges currently have temperatures readings, and these are only at one point, not highlighting the distribution of temperatures to users. Temperature and humidity within a fridge can vary; higher-temperature zones (better for storing drinks) form at the top and low-temperature zones (better for meat) at the bottom. Many people are unaware of the hotter and colder zones and where to store food optimally [57]. Food is often wasted by storing it incorrectly [102]. Smart fridges in the future could monitor shelf life and direct users to where to store food, possibly with a proven colour code system used in a previous study [103].

Some fridges use fans to distribute air around the fridge and even out the temperature distribution [104]. Studies have also shown temperature variations can be reduced by using PCM in the shelves although this reduces storage space [105]. Liebherr have a patent for a BioFresh technology which includes a temperature and humidity controlled draw which can keep food at a set low temperature [106], [107]. Purifying the air in the fridge has also been used by some manufactures, but there are no studies showing if this extends food life significantly [108]. One fridge concept identified proposes having a vacuum pack system built in to help store leftover food and preserve them [109].

Beko and Blomberg utilise blue light LEDs in the salad drawer of some of their fridges [110], [111]; this is designed to improve the shelf life of fruit and vegetables but has also been shown to have antibacterial benefits [112], [113]. Beko have more recently moved to a range of light colours used throughout the day (Harvest Fresh) [114]. UV light can also be used to self-clean fridges to help preserve food and liquids stored [97].

One of the most effective ways to reduce food waste in the future is likely to be with smart connected fridges used to monitor food inside the fridge, either by using cameras, weight sensors [115] or QR codes on food [5]. More recently, easier food tracking methods have been developed using AI, machine learning and image processing [116]. Knowledge of food in the fridge can provide useful information to help automatically plan meals, notify users of food going off and plan shopping via websites or apps [5] [6].

For developing or rural communities where power is unreliable, there are also PCM options to store thermal energy. An excellent example is technology from SureChill. Water surrounding the fridge compartment is frozen at the top; the fridge exploits the natural phenomenon that water is most dense at 4°C and less dense when warmer or colder, to create a fridge that stays close to 4°C [117] even in a power cut. SolarChill is an example of a solar powered fridge with ice thermal storage requiring no mains power [55].

3.6 Other features to reduce energy used

Estimates for extra energy consumption to cool fridges/freezers due to door opening vary from 1040% [118]–[120]. Many new designs for smart fridges are looking to utilise cameras or sensors to show users what is inside the fridge and keep it closed [5], [6]. LG used InstaView Door-in-Door which is a glass window designed to illuminate what is in the fridge when knocked on [121]. Concept designs of a fridge/freezer have been presented with smaller draws or compartments built in allow easy access to certain foods an drinks and avoid opening the whole fridge [122], [123]. It is not clear how much of a benefit these features have as it has not been studies.

3.7 Summary

Many different technologies have been discussed in this section. Many are already in use in refrigerators but may not have been widely adopted. A timeline of predicted technology development is shown in Fig. 5 based on the authors' evaluation. Technologies to the left of the timeline are more likely to occur sooner, while the right is high risk and lower readiness level technology.

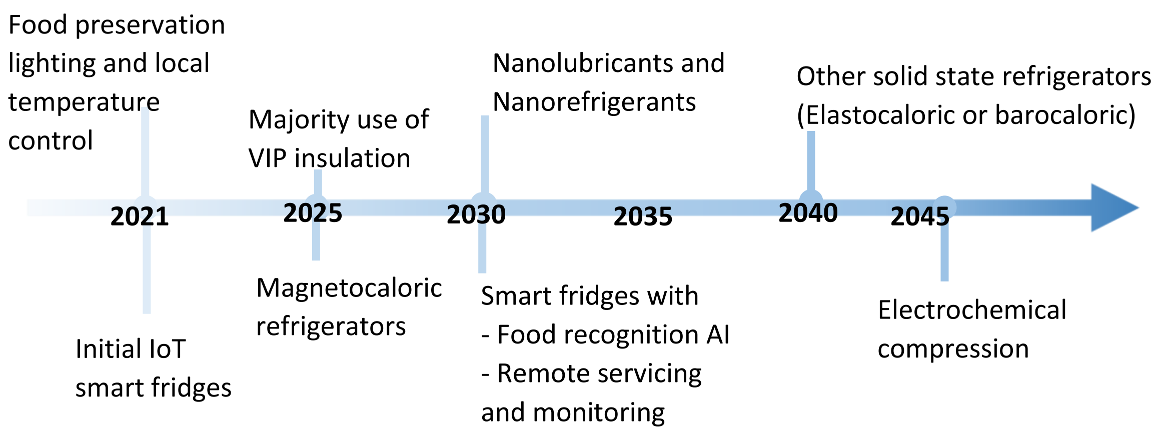

Fig. 5 – Timeline of predicted technology for fridges leading up to 2050. Based on authors' estimate using studies available.

4 Cookers – Hobs and oven

Two of the most common appliances found in people's homes are hobs and ovens. Research and developments in these two appliances are linked, hence why they are evaluated together. Historical evaluations of innovations in food and cooking have demonstrated that new cooking capabilities do not disrupt existing cooking methods and instead tends to be added to existing practices [124]. This is likely what will happen with any new cooking technology such as 3D printing food.

4.1 Energy supply

One of the biggest changes facing domestic cooking appliances is the change in energy supply. The finite supply of natural gas and pollution has led to a drive to reduce the UK's use. Two clear trends can be seen from this, either a transition to electric-powered appliances or hydrogen gas. A 2020 report for BEIS [125] already highlighted many of the social factors impacting a transition to electrical cooking appliances and provides more details on this topic.

4.1.1 Electrical powered

Currently, in the UK, there is still a preference for cooking with gas [125]. However, gas hobs are likely to be replaced with electrical heated ceramic and induction hobs as the government looks to reduce the use of natural gas [126]. Sales of electrical induction hobs have increased due to improved design and performance, safer operations, and better efficiency. Unlike gas or electrical heating hobs, induction hobs direct energy into the cooking vessel making, it a fast, efficient process. Flexibility in the size of coils has allowed designers to create induction surfaces that adjusts to the pan location and size to avoid loss of heating if a pan is moved [127]–[129]. In new kitchens and buildings, induction hobs are likely to be dominant as prices fall and efficiency is improved further. New designs are also likely to be movable and adaptable, such as the wall-mounted hobs from Fabita [130], see Fig. 6. Induction heating is not limited to hobs; some ovens, such as 6th SENSE Absolute Oven from Whirlpool [131], use an induction shelf to heat up oven pans. Comparisons of induction and gas hobs have shown a greater environmental impact from induction due to the rare materials used but also the source of electricity to power it [132]; as renewable energy sources increase, induction hobs will have a lower environmental impact.

Future induction hobs may not follow a flat plate design; concept designs include a magnetic clip-on induction 'Snail' [133] for pans or heated balls placed directly into the food in a pan [134]. These designs could be especially beneficial smaller flexible living spaces.

Fig. 6 – *Wall mounted induction hobs by Fabita,* image from [130].

4.2 Gas powered

Despite improvements to gas hob efficiency to avoid lost heat [135], [136], natural gas is still being phased out. One possible replacement for natural gas is hydrogen. A report from Frazer Nash for BEIS looked at converting the UK gas infrastructure to hydrogen [137]. For domestic hobs to use hydrogen, adjustments to the burner design will be needed to deal with flammability and high flame speed [138]; this could be built into new appliance design (e.g. duel-fuel designs), or conversion kits could be installed on existing appliances. The Hy4Heat project (currently ongoing) is looking at changes needed for domestic appliances to switch to hydrogen gas [139].

4.3 Changing cooking habits

The way we consume food in our society is changing. A recent report highlighted increasing trends of more home meal kits (Hello Fresh, Gusto, etc.) in the UK [19]; these prepared recipe boxes are often designed to be quick and easy to follow to save time. Cooking used to be a labour-intensive process that took hours and utilised multiple family members enabling cooking skills to be passed on. However, parents often do cooking alone and as quickly as possible, leaving little opportunity to pass on cooking skills [140]. Future connected IoT appliances may have to be the cooking teacher, directing the user with instructions, monitoring unattended food, and providing cooking tips as you cook.

Brava addressed many of these changes in their new oven design. It utilises infrared to heat up different zones quickly, removing the need for preheating and allowing multiple things to be cooked simultaneously at different rates. They combined their food delivery service and their smart ovens with pre-programed recipes to create a complete service. Users can rent ovens from them, order food and have it set to cook in the oven, speeding up, and automating cooking and shopping. This complete cooking and shopping service could expand to other appliances, with fridges which can recognise you are low on food and order it directly for you. There is also a greater number of people ordering food and eating out [19]. This may lower demand for multiple cooking appliances; consumers may choose to have only an oven or hobs, not both.

4.4 Automation or assistance with cooking

With advances in robotics, there has been increased interest in automating many cooking procedures. Examples include robot cooking arms with visual AI sold for commercial use by Miso Robotics [141] or domestic use by Moley in the UK [7] (see Fig. 7). These robotic arms are designed to operate in a known kitchen setup provided with the robot. Integration into existing kitchen designs and layouts will require more development but will likely be seen in the future. A key future challenge will be safely managing human interaction and coordinating while cooking with humans. The complexity of tasks possible will increase as sensors, computational power, and actuators improve.

Fig. 7 *– Automated cooking robot arms from Moley,* image from [7].

Users are unlikely to trust a robot to fully cook for them straight away; instead, domestic assisted cooking is likely to develop first. Cooking hobs and ovens are already being designed to provide more information and intricate data displays, either through built-in screens, visual projection or augmented reality [142]–[145]. These systems could provide feedback as you cook to help direct cooking, offer advice, give safety warnings, or tell users where utensils are. A recent study investigating technology for older adult as they cook highlighted that assisted technology would be much more useful than a fully automated system that would be harder to trust and integrate into daily cooking routines [10].

The other more recent development we are likely to see is cooking appliances which can recognise what we are cooking and its condition. Using this information, a hob or oven could automatically adjust temperature or humidity control as needed. These automated food monitoring systems could utilise smart taste sensors to provide suggestions to a user about seasoning or ingredients required [146], [147].

4.4.1 3D printing food

Additive manufacturing (also known as 3D printing) has received significant interest in many industries, including food. For food to be printable, either it has to come as in powder form for laser sintering printing or a paste/liquid which can be moved and set using extrusion [148], [149]. Some basic extrusion printers are already available commercially for printing chocolate, puree, liquids or mashes [150], [151]. These printers primary add customised 2D patens to dishes and can print some basic 3D shapes. More advance laser sintering sugar printers [152] that can print complex shapes have started to arrive.

One major drawback currently is that food has to be cooked before and types of food are limited (e.g. no raw meats) [153]. This has led to different research projects investigating new ways to cook food. Blue lasers were successfully tested to cook raw dough [154] and salmon [155], while radio waves have also been utilised to penetrate food packaging and heat foot to 70°C to kill bacteria [156]. Both these cooking methods have yet to be fully developed and proven reliable and safe. Other printers, such as PancakeBot, print directly onto a heated pan [151].

If cooking with 3D food printers becomes more common within homes, we could see food supplied as powders, or cartridges of puree, which can be loaded into a printer to be automatically cooked. These printers could be stand-alone appliances or included within existing hobs and ovens.

4.5 Summary

Many different technologies have been discussed in this section relating to cooking. A timeline of predicted technology development is shown in Fig. 8 based on the authors' evaluation. As with the previous timeline, technology predicted sooner is more certain and technology arriving later is less certain to be devloped. Despite a lot of research into hydrogen for cooking, it may prove to be easier and safer to transition to electric cooking instead.

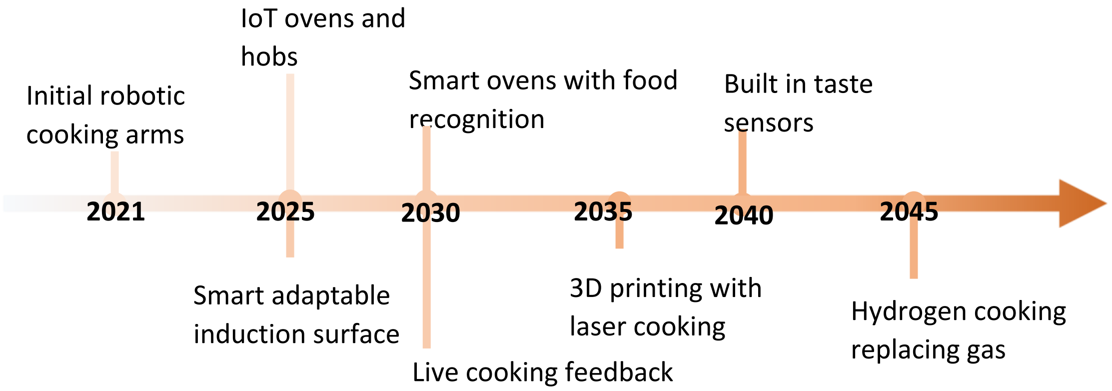

Fig. 8 - Timeline of predicted technology for cooking leading up to 2050. Based on the authors' estimate using studies available.

5 Washing machine and tumble dryer

5.1 Micro plastic

Up to 18,000,000 plastic micro-fibres can be released from 6kg of synthetic fabrics when washed [157], and 30% of micro-fibres in oceans are estimated to come from washing clothing [158]. Techniques to deal with it include filtering wastewater or using bags and balls in the wash to help catch them. No method has been shown to catch all fibres but Xeros's XFiltra filter and Guppyfriend washing bag performed best in recent tests [158]. Currently, most washing machines do not contain a micro-fibre filters but trials with XFiltra on domestic and commercial washing machines have just started [159]. There needs to be more advancement in filters, but also clothing fibres length and thickness should increase to help make them easier to filter and less likely to break off [160]. This problem is also not confined to washing machines, studies have found large quantities of these fibres outputs with tumble dryer exhausts [161].

5.2 Energy saving

The optimum way to reduce energy use in washing is to use low temperatures, though this leads to longer cycles which consumers do not often use [162]. The efficiency of appliances is often rated using these longer cycles, which in reality are not used. The energy used per washing machine tends to vary between countries depending on how often clothing is washed and standard regulating efficiency [163]; Europe has mostly moved to efficient horizontal washing machines designs.

Antibacterial clothing could help reduce the number of washing cycles needed; NASA has explored using antibacterial clothing on the space station to avoid the need for washing and drying facilities or daily clothing changes [164].

With more sensors and more computational power added to washing machines, new optimised washing cycles are likely to automatically adjust to the weight and type of clothing. Low-cost sensors and machine learning can be used to measure clothing weight [165] and adjust the cycle operation to be more efficient.

5.3 Alternative technologies

Using ultrasound waves in water creates cavitation (small air bubbles) and has been used in small cleaning devices; Dolfi is an example of one sold and is designed to be added to a sink or tub with clothing and detergent to clean the clothing [166]. A futuristic concept design used a similar method; a jelly-like substance is vibrated with ultrasound [167] (see Fig 9) cleaning the clothing without water.

Fig. 9- Concept design for vibrating jelly clothing cleaner, from [167]

UV light is also a common cleaning method in concept designs [168] and new washing machines [169]. UV light can also be used to make ozone (O_3); this is used for cleaning in Bosch [170] and Siemens sensoFresh [171] washing machines. Ozone (or active oxygen) cleaning can remove smell and bacteria from clothing, with or without water. Without water, the cleaning is not extensive, and only smell and bacteria are removed [164]. Using ozone could be useful for cleaning wearable electronics, which can degrade when washed in water [172]. Concept designs have also proposed cleaning using a jet of liquid carbon dioxide [173], [174]; however, this has not been tested.

5.4 Water saving technology

With climate change, many countries are experiencing water shortages, making it vital to reduce the water used. Xeros Technologies use beads of polymer (XOrbs™) which are added to the wash; they help clean clothing and reduce water needed by 70% and energy and chemicals by up to 50% [175]. XOrbs™ are being used in commercial washing machines and likely to be used in some domestic designs in the future. The impact of the balls on microfibers and long-term wear on parts has not been reported.

NASA have explored exposing clothing to vacuum pressures to kill bacteria and remove dirt and water [164]. However, this is harder to achieve on earth and does not fully clean the clothing. LG and Samsung recently released a cupboard with a steam cleaner to clean and iron clothing rather than putting it in the washing machine [176], [177]. This is an effective way to clean with less water if water is recycled but producing steam uses a lot of energy, and the cupboard is limited to only a few items at once. A filter developed from research at MIT is designed to remove grease and dirt in water but leave detergent, allowing water to be reused for washing multiple times; currently, developed by Aquafresco [178]. Lastly, LG washers have a smaller washing draw under the main one for smaller loads to save water (LG SideKick™) [179].

5.5 Clothes dryer

One of the most common methods of drying still used today is to heat air with a resistive heater and blow it across the clothes to dry them as they move. Hot air is then expelled, wasting heat and energy but expelling moisture.

5.5.1 Heat pumps

Efficient designs using heat pumps to heat and dehumidify the air, allowing the same air to cycle inside, have become more popular with up to 50% reduction in energy use. Heat pumps utilise VCC as in refrigeration but effectively reversed. Refrigerants utilised currently are HFCs; these are being phased out in favour of propane and carbon dioxide. Changes to existing heat pumps compressors might be needed to meet required compression ratios and flow rates [180]. Heat pump dryers recycle the same air through the evaporator and condenser to cool the air, remove water, and heat it up again, creating an efficient closed cycle where heat is not wasted out the exhaust. However, longer drying times and higher costs have slowed the uptake of heat pump based dryers. A closed air cycle could also make it easier to trap microfibers that can escape into the exhaust.

Existing exhaust pipes on tumble dryers can be fitted with heat exchangers to recover 55% of the heat for water heating [181]. Modelling investigated used a heat pump added to resistance heated tumble dryers to recuperate heat; savings of 50% were possible without reducing drying time [182], but these models do not consider all possible system losses likely to occur.

Alternative cooling methods used in refrigeration, such as thermoelectric heaters [183] (section 3.2.2) and sorption-based gas heating powered cycles [184] (section 3.3.3), have been tested. However, these have not shown notable efficiency improvements over VCC heat pumps.

5.5.2 Alternative drying methods

Vacuum drying has been tested in the food industry but not utilised for clothing until recently [185]. Vacuum dryers lower the pressure inside a chamber, lowering the temperature at which water will boil and evaporate. Morus is the first company promising a clothes dryer that uses vacuum drying [186], see Fig. 10. It promises to be smaller, 40% more efficient, use UV to kill bacteria, and dry clothes in only 15 minutes; although there is no set release date yet. Vacuum drying in current large dryer designs is too energyintensive, but future smaller vacuum dryers like Morus could be common in smaller living spaces.

Fig. 10 - Morus vacuum clothing dryer, image from [186].

Microwaves have been tested for drying clothing but over-exposure can occur easily and damage clothing, making it hard to control [187]. Another alternative method that has proven successful in tests is ultrasonic vibration from piezo-transducer modules [188]. However, speed and efficiency still need to be investigated further.

5.6 Summary

A timeline for predicted developments in washing machines and tumble dryers is shown below in Fig. 10.

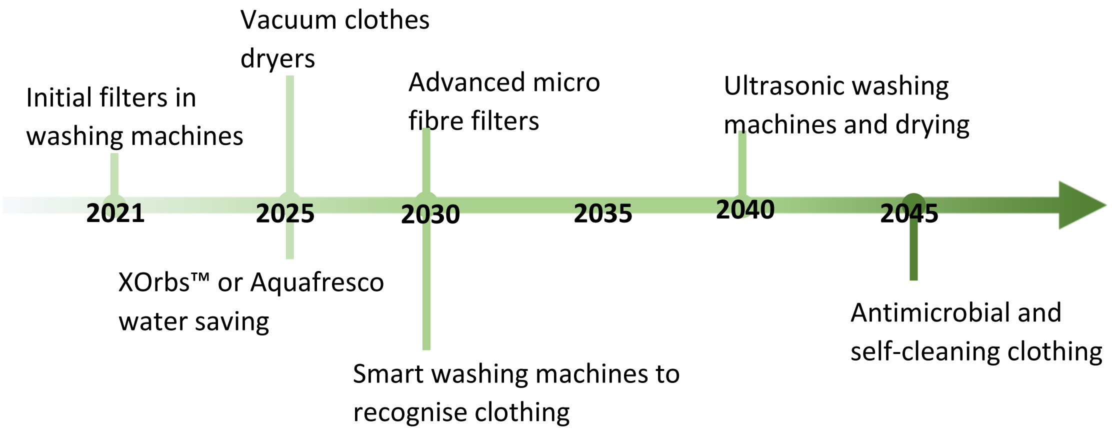

Fig. 11 - Timeline of predicted technology for washing and drying clothing leading up to 2050, based on the authors' estimate using studies available.

6 Industry consultation

6.1 Methodology

A further industry consultation was conducted as part of the research to ensure any industry perspectives were included. Four semi-structured interviews were conducted with industry professionals. Participants are kept anonymous, and any identifying information was removed. Questions and discussions mainly focused on fridges, but many of the trends apply to other LDAs. Questions focused on trends that were likely to be seen in 2050 and how technology could address the key challenges discussed at Fridge 2050. Only four participants were used in this analysis which limits the validity. However, further interviews will be conducted during the event to gather a wider range of opinions. The experience of the four participants was 31, 16, 16 and 15 years in either LDA manufacturing, small appliance manufacturing or related trade associations. Several key industry trends were identified from the four interviews; these are discussed in the following sections: connected appliances, reaching net zero, and safety and standards.

6.2 Connected appliances

Connected appliances was the theme most frequently discussed in interviews. These were defined as LDAs connected to manufacturers and users. A number of key uses are outlined below, which will come to the market in the next few years.

1. Predictive or preventative maintenance – All participants highlighted that connected appliances mean manufacturers can directly monitor appliances and use this to inform customers how their fridge is performing and when maintenance or repair is needed. Regular performance checks can be done remotely using built-in sensors. It was further noted that repairs could be performed remotely and autonomously without customers taking action. For example, software updates could be used to change a control system or optimise performance.
2. Provide feedback – Three participants noted that knowing consumers' use of their products can help inform better design of future LDAs. Data could be used to adjust users' behaviour to encourage sustainable practices (e.g. lower temperature washes). Notifications or nudges could also be sent to customers directly on their phones.
3. Prevent or assist product recalls – Three of the four participants said this was a key advantage of connected appliances. If a product has a fault, reaching all appliances is

currently difficult. With connected appliances, you can reach a larger number of appliances and send messages directly to customers. If customers do not return old appliances and continue to ignore product recall warnings, you can even take extreme action to remove these appliances' from operation remotely, as Samsung did with faulty phones. Connected appliances could improve the speed of recalls and the safety of appliances before they are recalled. This is an important trend that was not noted previously in the literature review.

4. Assist with disabilities – When asked about elderly or disabled users, two participants stated that connected appliances could help remove the need for buttons and enable appliances to be controlled by phones or voice activation.
5. Demand-side energy balancing – One participant said that connected appliances could help reduce peak loading on the grid.

6.3 Reaching net zero

The second theme discussed was the drive to net zero, as one participant said, "you can't have a conversation now about appliances and not talk about it". Key themes related to net zero are energy efficiency, circular economy, appliances sold as a service, changes in materials, and food waste.

6.3.1 Efficiency improvements

Participants described the industry as having made great improvements in efficiency, which have helped reduce CO_2 use. However, they were split on how much efficiency could improve; half felt that further smaller gains could be made while the other half thought we were approaching a limit of possible efficiency with our current technology. Two participants noted that the large developing markets (India, China and Africa) would be where the largest energy use is and that not all current appliances will suit these markets. Alternative power sources, such as solar-powered refrigerators, might need to be considered. It was also clear from the interviews that we need to ensure we are aware of the performance of our old appliances in relation to new ones. We can build appliances to last 30 years but that might not be the best option. Fridges from 30 years, ago are now worse for the environment than buying a new one. Also, users are likely to dispose of their fridge before 30 years, making extra resources used for the life-extension unnecessary.

Two participants mentioned that further efficiency could be gained by handing more control over to our smart connected appliances. For example, currently, people tend to use higher temperature faster washes for washing machines and dishwashers, but eco washes can be better for some clothes and the environment. A smart appliance could recognise what is placed inside and optimise itself to reduce energy. Removing control forces users to utilise the most efficient settings.

6.3.2 Circular economy

Participants said that manufacturers have previously focused on the use phase of their appliances but are now shifting to look at the whole lifecycle. Manufacturers are starting to think about "quality of appliances more than quantity", as one participant noted.

1. Manufacturing - Manufacturing is focused on becoming carbon neutral (as seen in Beko) and reducing energy and water used in production processes.
2. Transport – It is important to consider how products are delivered to the market, packaging used, and the supply chain of parts and materials.
3. Materials – Materials are more sustainably sourced, or manufacturers are looking at using recycled materials and reuse of old parts where possible.
4. Recycling appliances – Designs must be made easy to disassemble to recover key materials. Users need to be encouraged and educated to recycle appliances correctly. Gasses used in insulation and refrigeration are difficult to dispose of and need special handling, complicating the recycling process.

5. 3D printing parts for repairing – This was noted by two participants and could potentially be part of remanufacturing processes in the future.

Three of the participants noted that currently, fridge products benefit from not being upgraded frequently like phones or IT equipment. However, two participants pointed out a growing demand for large statement appliances (range cooker or American fridge/freezer); this is a dangerous trend as cooling air in an empty fridge wastes energy, and smaller appliances are often more suitable. This could be a bigger problem as more people order food and eat out leaving big fridges empty. There is also a problem that people often replace appliances when refitting kitchens, when they may still be useable. It is important to educate consumers about appropriate appliances and help them buy the most suitable appliance to help reduce energy and material usage.

6.3.3 Appliances sold as a service

Three participants mentioned appliances sold as a service as a way to reduce the environmental impact of LDAs. Participants thought maintenance and servicing could be included using connected appliances to prolong use and optimise efficiency. However, currently, there is no plan for manufacturers to sell products as a service. One participant highlighted that younger people might be more willing to accept a rental model. While another said that communally shared appliances would be better for the environment; although, currently, there is not much demand for this in the UK.

6.3.4 Change in materials

Several possible material changes were highlighted. One change includes the reduction of pentane gas as a blowing agent. A second change is that the percentage of recycled materials in fridges will increase. Lastly, two participants discussed bioplastics that could be sourced sustainably. However, this needs to be carefully managed as land used for plastic may be better used to feed people or preserve nature; also, recycling plants cannot handle bioplastics yet.

6.3.5 Food waste

Food waste was mentioned as a key problem and contributor to CO_2 by all participants. Currently, fridges play a vital role and participants highlighted that there had been a lot of work previously to reduce food waste with better temperature control and smart lighting. It was also highlighted that future appliances will likely be able to monitor food, using cameras or nose sensors, and remind us when it is going off. One participant also explained that we could have personalised products with capabilities to grow food.

6.4 Safety standards and regulations

As noted previously, participants all highlighted that connected appliances could improve safety by helping with recalls and regular product software updates. Participants also mentioned other features such as smart ovens that could turn off when not in use and smart tumble dryers could remind you to empty a full filter. Three participants said that it was important that the UK standards and regulations were not too strict as this would reduce customer choice in the market. Although they also said standards should be effective and reduce unsafe or environmentally damaging practices. Participants tended to favour domestic regulations and standards, staying close to global or EU counterparts, to ensure products made internationally can be sold in the UK.

7 Concluding remarks

Our society faces key challenges such as increasing elderly population, depleting resources, new diets and net-zero targets, as we approach 2050. Our LDAs will have to change to be future proof. The efficiency of LDAs has generally increased, but especially for fridges and freezers; greater efficiency has been driven by new technologies but also demanded by customers who have a heightened awareness of efficiency with product labelling. We need to ensure future efficiency benefits are affordable and available to a broad section of society, either with appliances sold as a service or by offering affordable upgrades with remanufacturing. Manufactures have played a key role in creating efficient LDAs; they should also take an active role in the end life of LDAs or support other organisations working on reusing (for more efficient models only), recycling and remanufacturing old LDAs. Efficiency and emission from transport, manufacturing and end of life need to be further improved to meet the net-zero target.

Smart connected appliances are growing in popularity and affordability. The long lifespan of LDAs and high cost are likely to lead to a gradual uptake of these smart appliances. Smart LDAs have the potential to simplify and further automate aspects of our life. However, they also have the potential to help us address environmental challenges. Our fridges could encourage us to eat sustainably or tell us food is going off, washing machines could adjust water or power depending on how dirty clothing is, and all LDAs could coordinate with the national grid to optimise when power is used.

VCC is still likely to dominate cooling technology in 2050 but with higher efficiency compressors and only HC gases. Other solid-state cooling refrigerators could be seen soon, though currently, these are not developed enough for widespread domestic use. New features to reduce door opening and feedback temperatures of the fridge to users can help prevent food waste. Oil-free linear compressors could be used more frequently when released. Compressors are also likely to run at variable speed rather than on-off to reduce power use and noise. VIP is expected to dominate insulation, though the ageing effect on all insulation needs further evaluation to ensure remanufactured or reused products still perform effectively.

Existing gas cooking appliances could be adapted to allow them to work on hydrogen in the future. However, energy efficient and affordable induction hobs are likely to increase in popularity. 3D printing and robots for cooking will become more common in domestic kitchens, which may change how food is sold. Slow uptake of previous cooking technology shows us robotics is unlikely to take over all kitchens. Many people will prefer less intrusive technology such as virtual cooking assistance to help provide directions and monitor food as you cook. Lastly, our clothes washers and dryers will have to catch microfibers as well as improving efficiency. Lower temperature and water use should be encouraged by utilising active oxygen or ultrasound technology to aid cleaning. While for drying, new heat pumps and vacuum dryers can help drive greater efficiency.

Improvements to existing designs should still be encouraged, including further research and concept designs for LDAs. The key technology for our Fridges in 2050 might not exist yet.

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