HyLink™ Technology-Readiness Level Assessment (TRLA)

Wellington, New Zealand

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HyLink™ Technology Readiness Level Assessment (TRLA)

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degree of Bachelor of Science

by
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Abstract

Most household thermal needs are currently met unsustainably via nonrenewable energy sources, that contribute to greenhouse gas emissions. To displace these emissions in certain high net-worth, fringe-of-grid markets, Callaghan Innovation is developing a hydrogen renewable energy system called HyLink™. In this study, we use a Technology Readiness Level Assessment (TRLA) to evaluate the market readiness of the. We tailored the TRLA criteria to fit the HyLink™ system. Based on data from user surveys, public surveys, and performance logs we concluded that HyLink™ can be classified as TRL 7. With a few recommended adjustments, the HyLink™ system can be further advanced to TRL 8.

Executive Summary

Renewable energy systems (RES) use naturally abundant energy sources such as wind, solar, hydroelectric, and geothermal to provide an environmentally friendly and sustainable method of energy production. This form of energy production can facilitate independence from fossil fuels, which rely on unsustainable hydrocarbon-based fuel sources that contribute to greenhouse gas emissions, namely in the form of carbon dioxide (CO2).

A large remaining contributor to carbon emissions stems from energy consumption in households. Many households use solid fuel, natural gas, or liquefied petroleum gas (LPG) for their thermal energy needs (e.g. space heating, water heating, and cooking) which make up approximately two-thirds of a household's total energy consumption (Isaacs, N., Saville-Smith, K., Camilleri, M., & Burrough, L., 2010). Alternative fuel sources, such as hydrogen gas, can function as clean sources of heat to meet this demand with minimal to no carbon-footprint. Callaghan Innovation, a government agency with a focus on facilitating innovation in business, is developing a hydrogen energy technology called HyLink™, which utilizes hydrogen gas to replace nonrenewable resources for thermal needs. HyLink™ is currently being designed for use in off-grid, fringe-of-grid, and high net-worth household systems where the marginal cost of attaining thermal fuels is high.

Callaghan Innovation is investigating the market readiness of a pilot installation of the HyLink™ system using the Technology Readiness Level Assessment (TRLA). The TRLA is a metric-based evaluation that is used to assess the risks and maturity of a specific technology on a scale of 1 to 9. The goal of this project is to facilitate further development of the HyLink™ system for mass production through the application of the TRLA. To that end, we have assessed the HyLink™ system at the Maori Innovation Hub, established a set of criteria for Technology Readiness Levels (TRLs) relevant to HyLink™, observed user experiences of the HyLink™ system, and used these sources of information to assess the current TRL of the HyLink™ system.

HyLink™ utilizes hydrogen gas electrolyzed from water to replace non-renewable resources for thermal needs. The system operates by connecting to a household's main source of electricity to power an alkaline electrolyser that produces oxygen gas and hydrogen gas from water. The oxygen is purged from the system, and the hydrogen is stored underground at relatively low pressure. This gas is then used as needed to meet household thermal demands such as space heating, water heating, and cooking; through direct combustion. The only byproduct created during combustion of hydrogen gas is water vapor, making it a clean and eco-friendly fuel.

An evaluation tool like TRLA can be helpful for assessing a technology's market readiness--especially in context with user experiences. The TRLA is a metric-based evaluation that is used to assess the risks and maturity of a specific technology on a scale of 1 to 9. This provides transparency and is useful for both investors and other companies. This assessment can "identify the gaps in testing, demonstration" of a technology, or if it is in need of "increased management" or "additional resources" (U.S. Department of Energy, 2013).

The description for each of the 9 individual technology readiness levels is presented below (see Figure A).

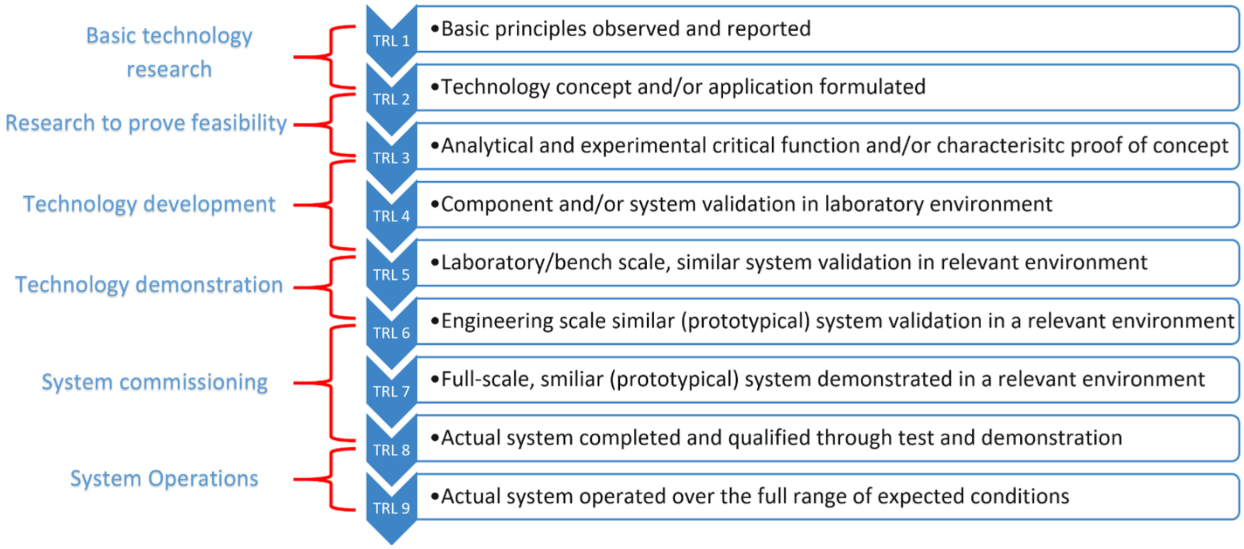

Figure A: Interpreted Technology Readiness Assessment Levels (U.S. Department of Energy, 2013)

The pilot HyLink™ system has previously been assessed to be TRL 6, and has now been prepared for another Technology-Readiness Level Assessment focused on TRL 7 and 8.

Approach and Key Findings

The goal of this project was to assess the TRL of the HyLink™ system. Evaluating the system with the TRLA benefits Callaghan Innovation by assessing the current maturity and market readiness of the technology. We proposed four objectives to accomplish our goal:

- *Objective 1: Assess the HyLink™ system at the MIH*
- *Objective 2: Establish a set of criteria for TRA levels 7 and 8 for HyLink™*
- *Objective 3: Assess the user experience of the HyLink™ system*
- *Objective 4: Assess the current TRL of the HyLink™ system*

To meet our objectives, we conducted a site assessment of the MIH and held open ended interviews with key experts. Using the observations from the site assessment and interviews, we created criteria for TRL 7 and 8 that accurately assess critical functions of the system. The creation of these criteria was an iterative process to ensure the integrity of the ruberic. We conducted a public survey to learn about average New Zealand home energy use, and a user survey to learn about perceptions and experiences with the HyLink™ system specifically. Finally, we compared the data obtained through the surveys and log data from the HyLink™ system to compare its capabilities to the criteria of TRL 7 and 8.

<u>TRL 7 Assessment:</u>

Technology Readiness Level 7 evaluates readiness in dimensions such as autonomy, maintenance, and overall efficiency. Using our own measurements gathered from parsing the HyLink™'s log files over the last year (February 2nd-December 29th 2016), in conjunction with a user survey, we found that the system meets the necessary criteria to fulfill TRL 7. The breakdown of each TRL 7 criteria for HyLink™ is shown below in Table A.

Table A Comprehensive TRL 7 Guidelines

TRL Question	Success and Qualification
Is the system fully autonomous in operation?	Yes
How many days of resilience does the HyLink™ system offer for an average New Zealand home?	1.41
What size tank would be required for a week's resilience (without economization)?	~11,000 L
What is the overall efficiency of the system?	68-75%
Does HyLink™ produce enough hydrogen to meet an average New Zealand household's average thermal energy needs?	Yes

TRL 8 Assessment:

A thorough framework of the TRL 8 criteria can be seen below in Table B.

Table B: Table Comprehensive TRL 8 Guidelines
**Success and Qualification needs explanation*

TRL Question	Success and Qualification
Do the appliances work well? (Simplicity, Ease of use, effectiveness/similarity to typical household appliances)	Yes*
How long does it take for hot water to come?	Range: 5-30 seconds Average: < 15 seconds Median: 15 seconds
Is the amount of hot water produced sufficient?	Yes; 76% users extremely satisfied.
Is the amount of hot water produced enough for an average household on a daily basis?	Yes*
Are the user experiences positive?	Yes*
Are there major differences in taste/speed when cooking via hydrogen gas vs electric/gas?	Yes*
Did you lose hot water at any time during use?	No
Did the hot water lose heat during use?	Yes*
Did the hob, grill, or smoker stop working during use?	Yes*

Did the hob, grill, or smoker lose effectiveness over the duration of use?	No
Did you use any electric powered items at night? (things that need to be plugged in)	No
Are there differences in usability in comparison to systems users are used to?	Yes*
Are the appliances easy to use? (Can the appliances be operated with minimal training or instruction)	Yes*
Do users perceive the system as fully functioning and usable?	No*

We used our user survey data to assess HyLink™ in three main categories: "How well do the appliances work?" (Simplicity, ease of use, effectiveness/similarity to typical household appliances), "Are the appliances easy to use?" (Can the appliances be operated with minimal training or instruction), and "Do the users perceive the system as fully functioning and usable." Using the results, we determined that HyLink™ has not yet achieved TRL 8, but can do so by achieving the following recommendations.

Recommendations for HyLink™ System Developers

1. **Heat warnings**. We recommend that overt heat warnings are integrated into the cooking appliances. Specifically, a red LED that turns on when hydrogen is flowing in the appliance would be sufficient to alert users that the appliance is on.
2. **Hydrogen flow**. An increase to the flow of hydrogen to both the hob and the barbecue will ensure that the small burner of the hob stays lit, and the barbecue cooks food faster, therefore making the appliances more effective.
3. **Software**. The current software of the system has proven to be quite resilient, but remaining vigilant for bugs and inexplicable software behaviors should remain a priority.

Conclusion

Based upon our analysis we recommend that HyLink™ now be rated above TRL 7. By compiling the system's log files that were produced over the past year, and comparing it to the public's average energy usage, we could conclude beyond reasonable doubt that HyLink™ could meet the energy demand for an average household of four. Furthermore, if our recommendations above are addressed, HyLink™ can achieve TRL 8 in the near future. For now, HyLink™ is making strides to become a viable alternative in a very niche market, but continued research and development with HyLink™ technology could result in progression towards replacing fossil fuels with a clean-burning fuel on a wider scale.

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Glossary of Acronyms

CO_2 - Carbon dioxide

DOE - Department of Energy

HEEP - Household Energy End-use Project

JREC - Johannesburg Renewable Energy Coalition

LPG - Liquefied-petroleum gas

MIH - Māori Innovation Hub

OECD - Organization for Economic Co-operation and Development

ppm - Parts per million

REEP - Renewable Energy and Efficiency Partnership

RES - Renewable energy system

TPES - Total Primary Energy Supply

TRA - Technology Readiness Assessment

TRL - Technology Readiness Level

TRLA - Technology Readiness Level Assessment

1.0 Introduction

Renewable energy systems (RES) use naturally abundant energy sources such as wind, solar, hydroelectric, and geothermal to provide an environmentally friendly and sustainable method of energy production. This form of energy production can facilitate independence from fossil fuels, which rely on unsustainable hydrocarbon-based fuel sources that contribute to greenhouse gas emissions, namely in the form of carbon dioxide (CO_2). In fact, evidence shows the CO_2-concentration in the atmosphere has drastically increased over the past fifty years from 315 parts-per-million (ppm) to over 400 ppm largely as a result of anthropogenic activities, especially the burning of fossil fuels. Historically this value had never risen above 300 ppm over the past half-million years (U.S. Department of Commerce, 2016).

In 2015, New Zealand produced 81% of its national electricity renewably, in an effort to negate its impact of carbon emissions (Energy in New Zealand, 2016). This means a large remaining contributor to carbon emissions stems from energy consumption in households. Many households use solid fuel, natural gas, or liquefied petroleum gas (LPG) for their thermal energy needs (e.g. space heating, water heating, and cooking) which make up approximately two-thirds of a household's total energy consumption (Isaacs, N., et al, 2010). The combustion of these fuels produces CO_2, and their consistent use in household thermal applications contributes to the excess of 81 million tonnes of CO_2-equivalent emissions produced per year in New Zealand alone (Greenhouse Gas Emission, 2016).

Alternative fuel sources, such as hydrogen gas, can function as clean sources of heat to meet this demand with minimal to no carbon-footprint. Callaghan Innovation, a government agency with a focus on facilitating innovation in business, is developing a hydrogen energy technology called HyLink™, which utilizes hydrogen gas electrolyzed from water to replace nonrenewable resources for thermal needs. HyLink™ is currently being designed for use in off-grid, fringe-of-grid, and high-end household systems, but it has potential to replace all residential hydrocarbon-based fuel sources.

Callaghan Innovation is investigating the market readiness of a pilot-plant of the HyLink™ system using the Technology Readiness Level Assessment (TRLA). The TRLA is a metric-based evaluation that is used to assess the risks and maturity of a specific technology on a scale of 1 to 9. The goal of this project is to facilitate further development of the HyLink™ system for mass production through the application of the TRLA. To that end, we have assessed the HyLink™

system at the Maori Innovation Hub, established a set of criteria for Technology Readiness Levels (TRLs) relevant to HyLink™, assessed user experiences of the HyLink™ system, and used these sources of information to assess the current TRL of the HyLink™ system.

2.0 Literature Review

This chapter describes the current state of renewable energy options in New Zealand. Specifically, we elucidate law and history relevant to the promotion of RESs in New Zealand, and explore the HyLink™ system's potential to replace commonly used nonrenewable systems in the residential sector. Finally, we analyze the use and purpose of the TRLA, and examine a detailed method as to how to tailor and apply the TRLA specifically to the HyLink™ system.

2.1 New Zealand's Commitment to Renewable Energy

To understand the relevance of HyLink™ in New Zealand, we examined several government policies toward renewable energy sources. New Zealand began its international commitment to a sustainable future in as early as December 2002 when it ratified the Kyoto Protocol. The Kyoto Protocol was the first international commitment for targeted reduction of greenhouse gas emissions, and required regular updates for national and regional energy strategies (Policy Issues on Energy and Climate Change, 2012). Since then, New Zealand has joined several other international organizations and agreements. Two such organizations are the Johannesburg Renewable Energy Coalition (JREC) and the Renewable Energy and Efficiency Partnership (REEP) (International Energy Agency, 2015). These committees aim to allocate more funding into researching renewable energy sources. In accordance with these agreements and organizations, energy options such as solar, wind, geothermal, and hydroelectric power have paved the way toward renewability. That being said, full displacement of hydrocarbon-based fuels continues to be an immense challenge. As shown below in Figure 1, the majority of New Zealand's Total Primary Energy Supply (TPES) still comes from hydrocarbon fuel sources.

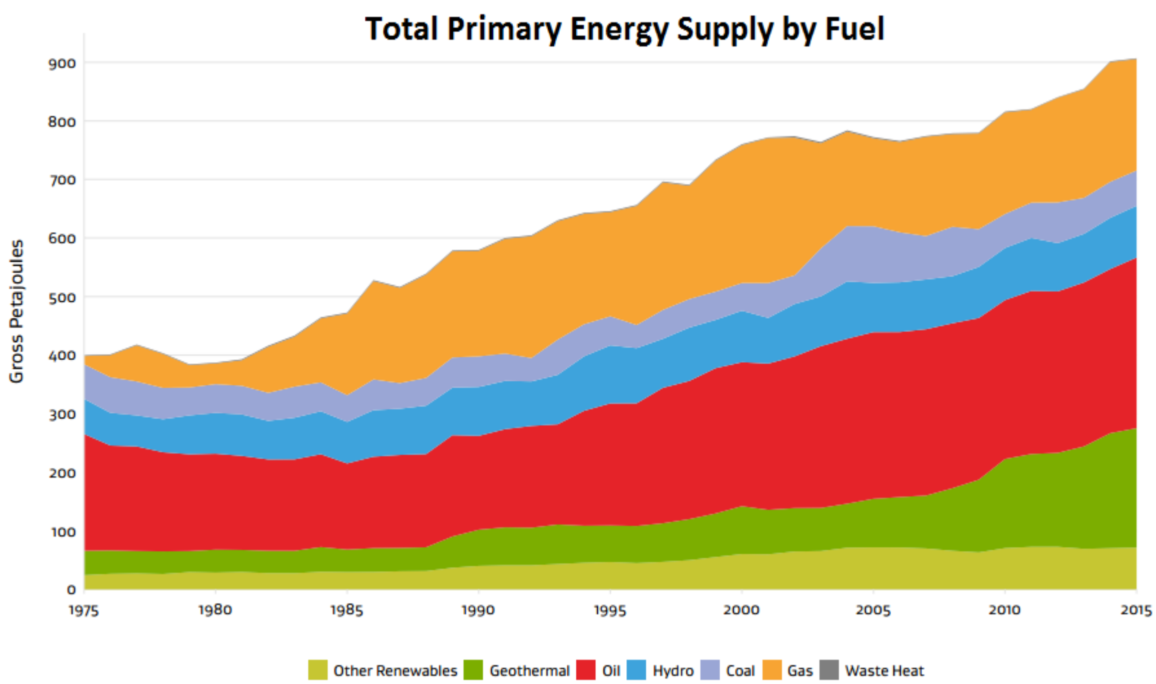


Figure 1: Total Primary Energy Supply relative to fuel-source (IEA, 2015)

To counter the continued dependence on oil, coal, and gas (propane, liquefied-petrolium gas (LPG) and natural gas or methane), the New Zealand government is taking more steps to increase the proportion of national energy production from renewable sources. This continuous effort resulted in a record 40.1% of all energy (thermal and electrical) being produced renewably in 2015 (Energy in New Zealand, 2016). This percentage is reasonably high and according to the Ministry of Business, Innovation and Employment, "New Zealand has the third highest contribution of renewable energy to TPES in the Organization for Economic Cooperation and Development (OECD), behind Iceland and Norway" (Energy in New Zealand, 2016). Much of this is due to the fact that 80% of New Zealand's electricity is produced renewably. The government has indicated its goal is to increase this share to 90% of electricity by 2025 (Energy in New Zealand, 2016).

2.2 New Zealand's Residential Sector

With a population of 4.5 million, New Zealand's residential sector consumes 11% of the national TPES, compared with 38% consumed in transportation and 36% in the industrial sector (Figure 2), (Energy in New Zealand, 2016). This 11% of national energy used in the residential sector makes up a significant portion of energy that is often supplied non-renewably.

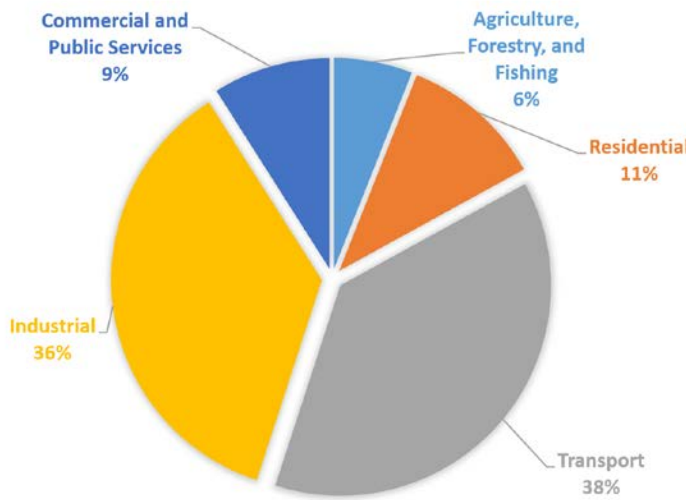


Figure 2: New Zealand Consumer Energy Demand by Sector (IEA, 2015)

The power consumed by a household in the residential sector can be further broken down into electrical and thermal demand. Thermal demands consist primarily of space heating, water heating, and cooking appliances, and makes up 69% of an average household's energy usage (Gardiner, 2013). The remaining energy is used to power strictly electrical appliances. Some households use electricity as a source for both their electrical and thermal needs, but 31% of households use solid fuel, LPG, or natural gas to meet the thermal needs (the distribution can be seen in Figure 3 below). These fuel sources are hydrocarbon based and their combustion contributes to unwanted greenhouse emissions.

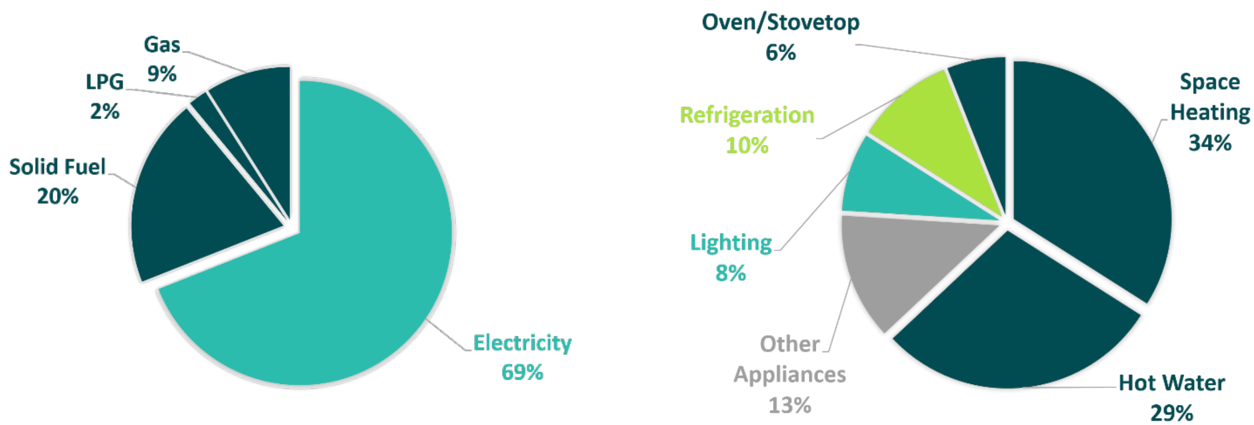


Figure 3: Energy Fuel and End Use in New Zealand Homes (NZ Home Energy, 2007)

New Zealand's ongoing endeavors to create a fully sustainable future include increasing the amount of renewable energy sources used in all sectors of the economy, including the residential sector. Two significant obstacles are that nonrenewable fuels are still widely used in households to produce thermal energy, and the cost to replace a household's thermal system is often too expensive. Therefore, typical homeowners are unlikely to adopt new RESs because the cost is too high with a small market, and they would thus continue to use their current nonrenewable system.

There are certain markets, however, where it is actually more favorable to invest in and adopt RESs early. One of these markets consists of high net worth individuals who live connected to the national electric grid, but are vulnerable to interruptions (e.g., wind damage). Another significant market is the fringe-of-grid. Fringe-of-grid is a loosely defined term referring to households located near the edge of the national electric grid where the incoming power from the grid is more limited than in central locations of the grid. This means that on the fringe-of-grid there may not be enough electricity available to perform thermal processes; such as in an electric water heater (McNicol, 2015).These two situations can result in considerable costs to acquire thermal fuels. Individuals that fall into these categories may find it reasonable to invest in a thermal RES to save money on alternative fuels and simultaneously decrease their carbon footprint. A tertiary market would be those who already possess a solar RES installation, but only actually use a fraction of their total available energy potential. This market consists of those who waste energy because they lack an adequate energy storage system. A market also exists of those If thermal RESs were to prove successful within any of these markets, there would be a better chance of widespread adoption of and subsequently lower carbon emissions from the residential sector.

2.3 The HyLink™ System

HyLink™ is an emerging RES that creates and burns hydrogen instead of a hydrocarbon-based fuel to provide a household with thermal energy. The current goal of HyLink™ is to replace solid fuel, LPG, and natural gas used by the viable markets described above. Ultimately, however, HyLink™ is meant to pave the way for thermal RESs to displace the reliance on hydrocarbon-based fuels in all of the residential sector.

2.3.1 How it works

The system operates by connecting to a household's main source of electricity to power an alkaline electrolyser that produces oxygen and hydrogen gas from water. The oxygen is purged from the system, and the hydrogen is stored underground at low pressure. This gas is then used as needed to meet thermal demands of a household such as space heating, water heating, and cooking through direct combustion. The only byproduct of hydrogen combustion is water vapor, therefore HyLink™ does not produce harmful greenhouse gasses. A simplified diagram of the HyLink™ system is shown below in Figure 4 to better illustrate the system's processes.

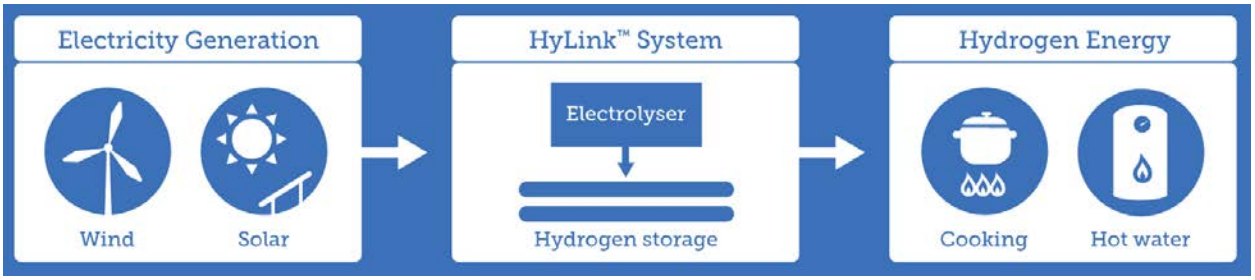


Figure 4: Process-flow Diagram of the HyLink™ Energy System

Additionally, HyLink™ can interface with existing electrical RES such as wind or solar as shown in the diagram to create a fully sustainable residence.

2.3.2 The HyLink™ Pilot Systems

Callaghan Innovation has so far built two separate HyLink™ systems. The first was built on Matiu/Somes Island in Wellington Harbor. This system was a prototype and functions as a proof of concept as it is utilized in an off-grid, remote location with minimal human interaction. The second installment of the HyLink™ system is located in Callaghan Innovation's own Māori Innovation Hub (MIH), (in Māori, Te Whare a Māui, a "working space for Māori businesses") in Gracefield--an industrial suburb of Lower Hutt, New Zealand (see Figure 5).

Figure 5: The Maori Innovation Hub

The MIH has the necessary tools to perform research, interact with locals, and develop technologies (Callaghan Innovation, 2016). One of the main focuses of this hub is to provide opportunities for cooperation between Māori businesses and innovators. HyLink™ is the main technology currently being developed at the MIH. Its lavatory and outdoor facilities are powered entirely by the HyLink™ system. This includes the site's hot water via an instant hydrogen water heater, and outdoor cooking appliances such as a barbeque, a two-ring cooking hob (with a small burner and large burner) and a smoker. These appliances operate by burning hydrogen gas directly.

2.4 The TRLA and its Implementation

In order to move from the prototyping stage to production, and eventually mass-production, a non-subjective and unbiased system for assessing a technology's maturity in terms of market readiness is necessary. This assessment rubric is known as the TRLA. It acts as a metric-based standard that can be used to measure how far along a technology's development is and how close it is to being commercialized. This provides transparency and is useful for both investors and other companies. This assessment may also "identify the gaps in testing, demonstration" of a technology, or if it is in need of "increased management" or "additional resources" (U.S. Department of Energy, 2013). There are 9 individual TRLs, and a description for each is presented below (see Figure 6).

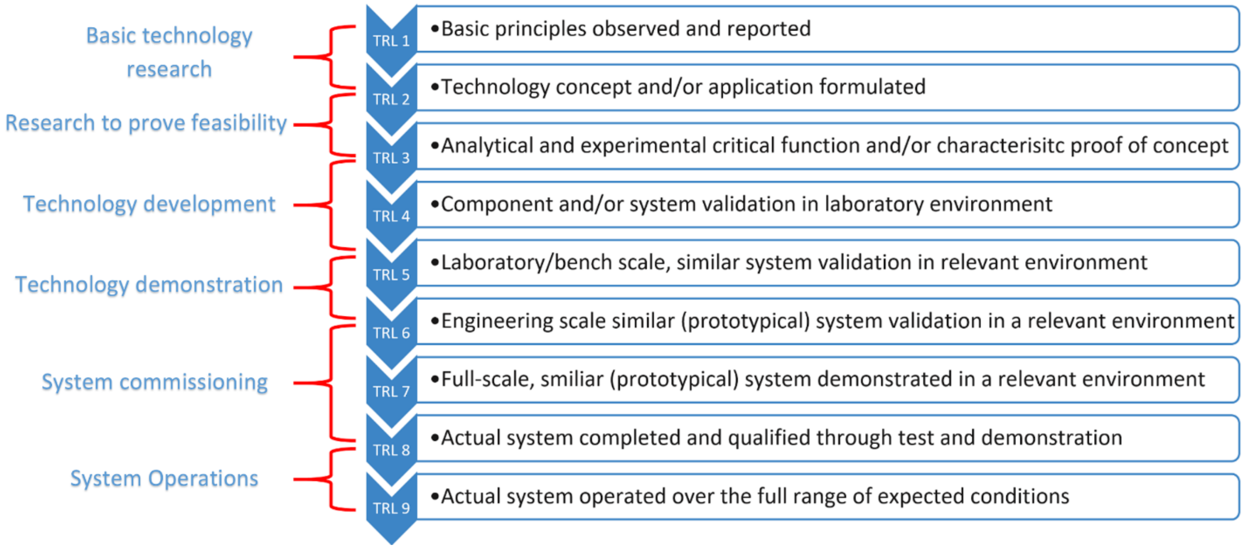


Figure 6: Interpreted Technology Readiness Assessment Levels (U.S. Department of Energy, 2013)

It is important to note that a TRL is not appropriate for the purpose of comparing technologies as it does not indicate how difficult it is to make advancements in terms of maturity. These difficulties can include risks, time, and other contextual factors associated with development. Additionally it may be easier to advance a technology from a lower TRL (e.g. 2) than it is to develop at a higher TRL (e.g., 7) or vice versa. There are many variations and uses of the TRLA. For the purposes of our analysis, we will use the U.S. Department of Energy (DOE) interpretation. It is based on 9 levels of assessment, where TRL 1-6 are qualitative and represent the prototype-phase of a technology, and TRL 7-9 are metric-based and assess the full-scale feasibility of the particular system in question. The pilot HyLink™ system has previously been assessed to fulfill TRL 6, and has now been prepared for another TRLA focused on TRL 7 and 8.

In order for a technology to receive a TRLA, the system must first have an anticipated TRL estimated from the general top-level questions in order to provide a starting point for the assessment and to provide the team with a basic understanding of the system's capabilities. The assessment begins at one level below the anticipated TRL to ensure the estimate of the technology's TRL is correct (U.S. Department of Energy, 2013). Critical functions of the technology related to the top-level question are then identified. These critical functions are tested individually to determine if they perform at the level required by the TRL in question. If successful, the technology can be officially classified to have reached that TRL.

3.0 Methodology

The goal of this project was to assess the Technology Readiness Level of the HyLink™ system. Evaluating the system with the TRLA benefits Callaghan Innovation by providing transparency and insight into the overall market readiness of the technology. We proposed four objectives to accomplish our goal:

- *Objective 1: Assess the HyLink™ system at the MIH*
- *Objective 2: Establish a set of criteria for TRA levels 7 and 8 for HyLink™*
- *Objective 3: Assess the user experience of the HyLink™ system*
- *Objective 4: Assess the current TRL of the HyLink™ system*

3.1 Objective 1: Preliminary assessment of the HyLink™ system at the MIH

Upon arriving at Callaghan Innovation, we performed a preliminary site assessment to better understand the current implementation of the HyLink™ system. This assessment included a tour of the MIH, and its corresponding HyLink™ facilities. We started outside the building, specifically noting and taking pictures of each HyLink™ appliance. This investigation included both the technical devices (i.e. the electrolyser), and the hydrogen appliances. We continued the investigation inside the MIH. We specifically noted the locations and content of all promotional material of the HyLink™ system within the building. We observed and photographed the locations of all indoor hydrogen appliances (i.e. water basins and showers). Finally, we recorded the location of the current user survey. This information was compiled to allow us to create an improved arrangement of surveys and promotional material within the building.

We held open-ended discussions with Robert Holt, the primary developer of the HyLink™ system, to learn about the technical processes. During these discussions, we recorded pertinent information related to the TRLA and the HyLink™ system's successes and shortcomings.

3.2 Objective 2: Establish a set of criteria for TRA levels 7 and 8

Using the DOE's TRL 7 and 8 definitions, we created and adapted our own success criteria tailored specifically to the HyLink™ system. This was done by determining questions for each level that, when answered, would sufficiently fulfill the DOE definition. Both the DOE's general rubric for TRL 7 and 8, as well as our success criteria of TRL 7 and 8 for the HyLink™ system are shown in Table 1 below.

Table 1: General TRL 7 & 8 Definitions and our TRL 7 & 8 Rubric Variations for Success Criteria

TRL 7 (DOE)	**Integrated Pilot System Demonstrated: System/process prototype demonstration in an operational environment (integrated pilot system level).**
Our TRL 7 Success Criteria	**"Demonstration (under operational conditions in a relevant environment) of the autonomous production of hydrogen by electrolysis and its use in appliances."**
TRL 8 (DOE)	**System Incorporated in Commercial Design: Actual system/process completed and qualified pre-commercial demonstration**
Our TRL 8 Success Criteria	**Real life usability demonstrated in a relevant environment in context with user experiences."**

Using these definitions, specific questions were designed to provide a more in-depth review of whether HyLink™ had sufficiently fulfilled each criteria (see Appendices A and B).

We broke down the TRL 7 success criteria into several questions that utilized technical data of the HyLink™ system, as well as public survey data to determine whether HyLink™ is technically capable of providing enough hydrogen for the end user. We repeated a similar process for the TRL 8 criteria. However, the TRL 8 success criteria, "Real life usability demonstrated in a relevant environment in context with user experiences" required that several more comprehensive criteria be formed to prove that the system can be used by an average homeowner. To create these criteria, each appliance powered by HyLink™ was examined individually. For each appliance, we considered all functions typical of the appliance (i.e. for a water basin, the temperature of the water, the speed of the hot water, and how long the hot water lasts, etc. are all the functions we analyzed). This way we were able to examine the usability of every appliance of the HyLink™. The finalized criteria were reviewed by our project team and advisors in an iterative process to ensure that the final TRLA criteria had maximum integrity and minimal bias.

3.3 Objective 3: Assess the user experience of the HyLink™ system

To answer the questions proposed to prove the TRL 7 and 8 criteria, we collected data about public usage of thermal energy systems and about user experiences of the HyLink™ system.

We improved the brief methodological survey that was in use near the lavatory in the Maori Innovation Hub (see Appendix C). We replaced many of the subjective questions with quantitative questions, and added questions regarding the quality and ease of use of the hot water and cooking appliances. We placed the improved surveys outside the lavatory. In addition, we incorporated flyers alongside the surveys that informs the user about the hot water appliances are powered by a hydrogen water heater in use at the site, and encourages the user to participate in the survey.

To collect further results, we invited a group of 20 students to an event at the MIH on February 8, 2017. This way we were able to collect additional user data for the HyLink™ appliances from our peers. We were also able to prompt our peers to note their observations of the hot water appliances in terms of water temperature, temperature control, duration for hot water to be produced, and differences in water pressure; therefore specifically targeting our TRL 8 criteria. We also asked a sample of experienced users of cooking systems, such as barbecues and hobs, to test and comment on their comparative impression of the HyLink™ cooking appliances.

In order to examine the HyLink™ system with regards to our TRL 7 criteria, we collected data about average New Zealand household thermal energy usage, as well as technical data about HyLink™'s production of energy over time. First, we modified and implemented a public survey created by the WPI group that worked with Callaghan Innovation in 2015 (Appendix B). The previous survey contained questions about New Zealand residents' current thermal energy source (LPG, solid fuel, natural gas, RES), and perceptions of hydrogen energy in general. We altered the questions to instead focus on general energy consumption and thermal energy practices (e.g. how long do you shower on average?). Once the survey questions were created, we pretested the survey on a sample of pedestrians in the Wellington Library, and consequently edited the survey questions to be more effective. With the completed survey, we returned to various locations around Wellington and conducted a convenience sample with interested pedestrians. Specifically, all four group members went to the Wellington harbor, the Wellington train station, the Wellington city library during the day to collect data. While there, each group member asked for participants in the survey and manually recorded their answers on a recording sheet. The data collected was entered onto Qualtrics for easier compilation. After several days of active surveying, we posted the Qualtrics survey to several New Zealand specific Reddit webpages to both increase our overall quantity of survey responses, as well as to diversify our participant demographic. This ensured that our results did not come strictly from Wellington residents.

In order to gain the technical data required to prove TRL 7, we analyzed archival data from the system log files of the HyLink™ system over the last year to look for the average rate of hydrogen production using a skimming/parsing algorithm. Using the electrical consumption data from the Household Energy End-Use Project (HEEP) and census data allowed us to calculate the average thermal energy usage over a year per occupied household. Using a simple conversion factor, representing the amount of energy a kilogram of hydrogen has, we were able to relate the two datasets and determine if HyLink™ could maintain the average thermal energy consumption of an average New Zealand household.

3.4 Objective 4: Assess the current TRL of the HyLink™ system

Once all survey data was collected, we utilized the TRLA criteria determined in Objective 2 and determined the current TRL of the HyLink™ system. We started by analyzing the technical data of the HyLink™ system along with the public survey data to compare to our criteria for TRL 7. Subsequently, we used the survey results from the MIH site as well as select results from the public survey to analyze the criteria for TRL 8. Once we determined whether the HyLink™ system did or did not meet every criteria for both TRL 7 and 8, we concluded the final current TRL of the system. In order to be considered a certain TRA level, a technology must already meet all criteria of the previous level; therefore, HyLink™ was required to be confirmed as TRL 7 before it could be considered for TRL 8.

4.0 Results and Discussion

Part 1. Results

We compiled our findings, arranged below by objective. These are derived from our own observations of the HyLink™ system, and combined with surveys from 99 members of the general public and 19 users of the HyLink™ system.

4.1 Objective 1. Preliminary assessment of the HyLink™ system at the MIH

Our tour and site assessment of the Maori Innovation Hub revealed the true arrangement of the HyLink™ appliances (see Figure 7a). The HyLink™ system consists of a water electrolyser contained in an enclosed box by the side of the MIH as seen in Figure 7b below. The electrolyser is fueled using the combined renewable energy produced from two wind turbines, and eight photovoltaic solar panels located on the roof of the MIH. A water heater is attached to the outside wall of the building, and the storage tank is located beneath a large concrete slab off to the side of the building (see Figure 7b). The purpose of the concrete is to mark, cover and protect the underground hydrogen storage unit. Another feature of the system is a battery located next to the electrolyser that is used only briefly to start the system and can be seen within Figures 7a, 7b, and 7c. In an operational setting, all of these components are not meant to be managed by an average user, because the complexity of the circuits and the electrolyser means that the system would best be operated near-autonomously.

Figure 7a: Front entrance of Maori Innovation Hub

Figure 7b: HyLink™ electrolyser

Figure 7c: HyLink™ battery
Figure 7: HyLink™ system components

The HyLink™ system components are configured near each other at our test site for observation purposes. To further facilitate this, there are control panels for the system mounted to the wall near the entrance to the MIH for basic monitoring and management of the system as shown in Figure 8, below. These control panels are located next to the entrance away from the other system components to be more conveniently placed for user access.

Figure 8: Control Panel at Entrance of MIH

The hydrogen water heater is responsible for heating two water basins and one shower in the lavatory inside the MIH building. There are also three hydrogen taps on the back deck of the building that are capable of connecting to devices that burn hydrogen. There are three devices used as a proof of concept for hydrogen cooking; a hydrogen-powered grill, a smoker, and a two-burner hob.

The site assessment inside the building showed us that prior assessments were limited to a single poster on the wall near the restroom that described an overview of the HyLink™ system and hydrogen technology in general. There were no explanatory materials for the HyLink™ near the actual hot water appliances, and no message to prompt users to respond with their experiences using the system.

4.2 Objective 2. Establish a set of criteria for TRA levels 7 and 8

During our discussions with the system developer, Robert Holt, we received the report proving that HyLink™ had previously successfully achieved TRL 6. Holt also explained that the main purpose of TRL 7 is to examine how well the HyLink™ system functions in terms of hydrogen production, and that the main purpose of TRL 8 is to examine the real life usability of the system. These definitions align with the DOE's general definitions of the respective TRA levels, and were used as a baseline to create more detailed criteria to assess HyLink™.

The success criteria for TRL 7, "Demonstration (under operational conditions in a relevant environment) of the autonomous production of hydrogen by electrolysis and its use in appliances," consists of two separate central criteria. The first requires that the HyLink™ system to function near autonomously. This means that the system should produce, store, and use hydrogen without any commands from a user. This also requires that the system should be run resiliently for an extended period of time. We decided that to demonstrate this capacity, HyLink™ should perform autonomously for at least 6 weeks while we collected data on the system. This time frame allowed us to observe the system during our time working at the MIH, and it is a long enough stretch of time to indicate the potential that the HyLink™ system could run on its own indefinitely.

The second central criteria for TRL 7 (contained within the general success criteria), requires that during autonomous operation, the HyLink™ system produces enough hydrogen to be used by an average residence. We used data from the Household Energy End-use Project and the census in addition to averages our public survey to ascertain an average New Zealand household's thermal energy use, and compared this to the hydrogen production from the HyLink™ system.

The main success criteria for TRL 8, "Real Life usability demonstrated in a relevant environment," was broken down into several explicit criteria to more accurately assess the different components of the HyLink™ system. Several questions were posed about each function of the HyLink™ system at the MIH site (e.g. water heating and cooking). These questions, when answered, either prove or disprove the main success criteria of TRL 8. All the questions and criteria for both TRL 7 and 8 are presented in full detail in Appendix A.

4.3 Objective 3. Assess the User-experience of the HyLink™ system

To meet Objective 3, we compiled responses gained from our user-experience survey and created graphics to display the data. The survey was divided into two sections: hot water and cooking with the questions focusing on comparing HyLink™ to traditional household appliances.

4.3.1 Data for User experiences

Through this study, findings emerged inductively that we used to support or refute the HyLink™ system's candidacy for TRL 8. We surveyed 19 of our peers and asked them to give feedback on their experience while using the HyLink™ system's appliances. These participants were asked to pay specific attention to the time lag of hot water production, temperature and temperature control, and the effects of using multiple hot water appliances simultaneously.

The first question of the user-experience survey asks the participant to evaluate their level of satisfaction with the temperature of the hot water (see Figure 9).

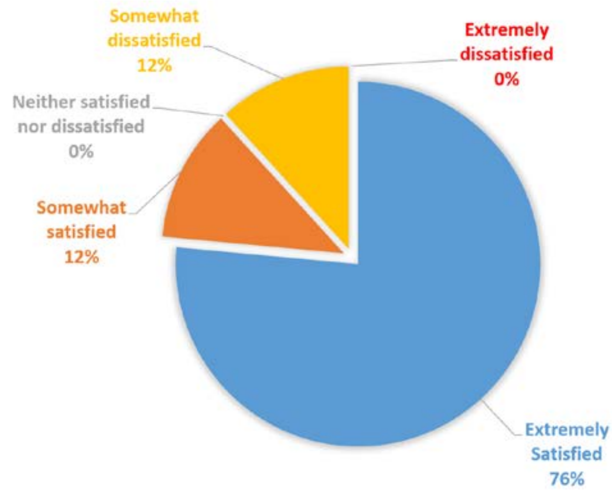


Figure 9: Q4 - Satisfaction with Hot Water Delivery at MIH (n = 17)

The scale for responses ranged from extremely satisfied to extremely dissatisfied. The large majority of responses were "extremely satisfied" with 76% of participants responding this way, and another 12% reporting being "somewhat satisfied".

We asked users to approximate their wait for hot water. Responses ranged between 5-30 seconds, with an average of less than 15 seconds, and a median response of 15 seconds.

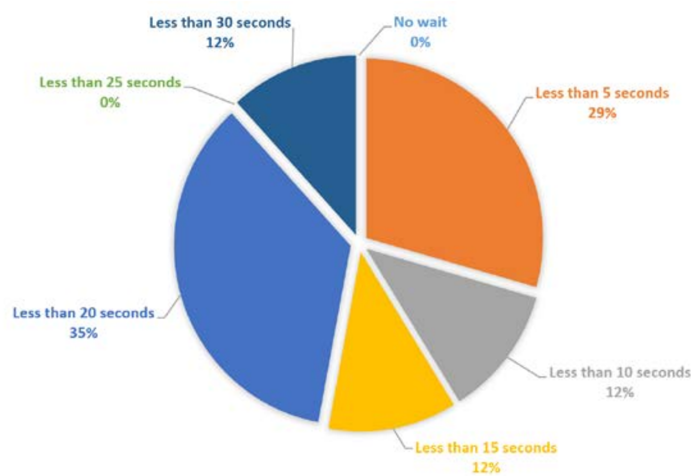


Figure 10: Q3- Time of Wait for Hot Water (n = 17)

Our questions asking for user satisfaction with cooking appliances was met with variable response. The data below shows a large percentage of people expressing some level of dissatisfaction with the cooking appliances.

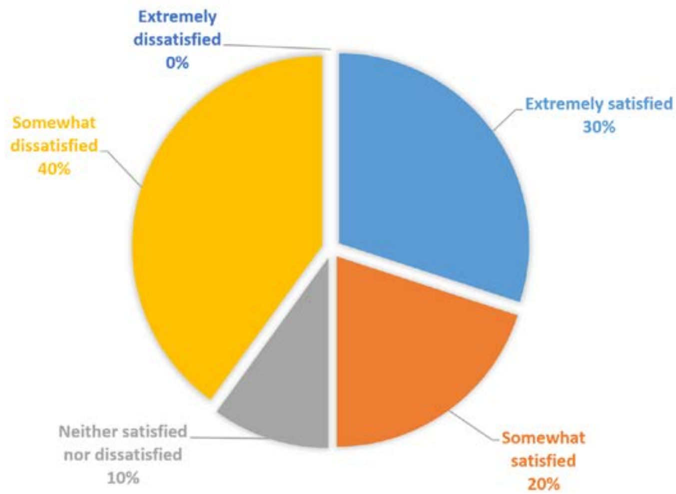


Figure 11: Q11 - Cooking Satisfaction at MIH (n = 10)

Although 30% of responses were extremely satisfied with the cooking appliances, the median response was somewhat dissatisfied with 40% of responses. This discrepancy shows some limitations with the survey. Based upon additional comment sections in our survey we discovered that the primary reason for dissatisfaction was that users believed the overall temperature of the cooking appliances was too low, and thus the cooking process took too much time.

4.3.2 Data from Public Surveys

A public survey was created based on TRL 8 questions established in Objective 3. The data gathered from our public survey is divided into sections: demographic information, household information, household energy and fuel usage, and electrical consumption. The survey was designed to estimate typical household energy use, perception, and preferences; and data collected was compared to publicly available census data.

We found value in collecting demographic information so that the system's fuel storage size can be adjusted for its intended establishment (see Figure 12). The data shows a large age distribution with the majority matching one of our target demographic (owning homes in a rural or suburban area).

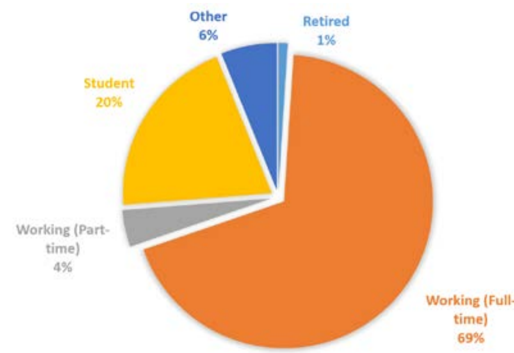
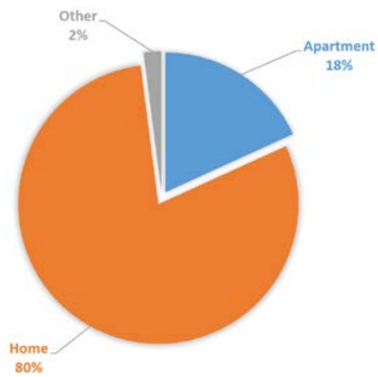
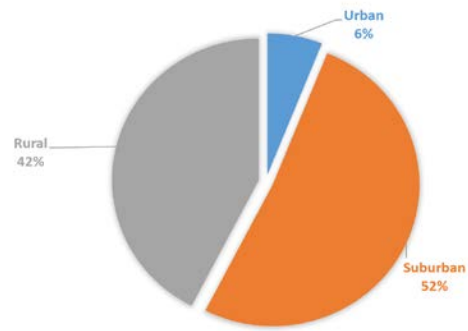


Figure 12a: Q4- Ownership of Primary Residence 2 Figure 12b: Q2- Participant





Occupation Figure 12c: Q5- Apartment or House Figure 12d: Q6- Neighborhood Type

Figure 12: Demographic Information from Public Survey (n = 99)

Our local responses vary slightly from the national New Zealand average in which 33% rent and 65% own (Statistics New Zealand, 2015). We found that the majority of responses worked full-time, lived in an owned home, in a suburban location.

Below is the data for our average participant age (see Figure 13). We also found it necessary to compare our sample to the overall New Zealand demographic to see if it is an accurate representation of the larger population, and thus a more viable method of extrapolating data.

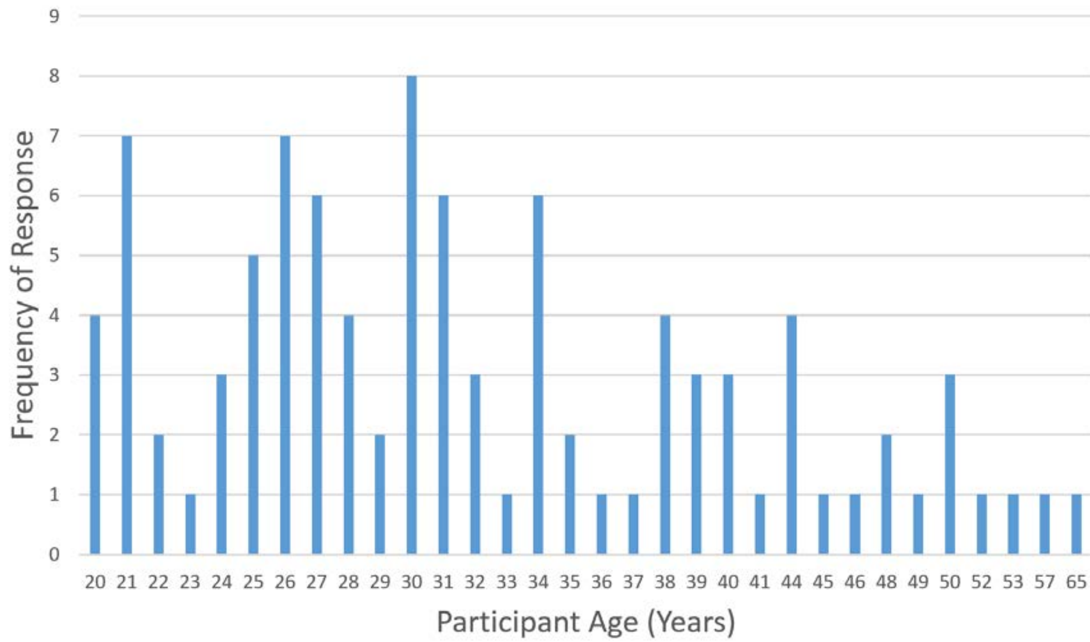


Figure 13: Q1- Population Distribution of Public Survey (n = 96)

The average response for age in our survey was 32.5 years old and the median age was 30 years old, so there were more responses from relatively younger people. According to Statistics New Zealand 2015 the average age of a New Zealander is 37.5 years. We find that our data is still viable because people who own apartments now are likely to own houses/personal residences in the future, and thus they could potentially consider installing an RES system like HyLink™ in their future residence.

The charts below represent data collected on household thermal energy. Our findings show that the majority of respondents currently use electricity for space heating (Figure 14a), stove surfaces (Figure 14b), water heating (Figure 14c), and ovens (Figure 14d). The majority of respondents also indicated they preferred electric ovens (Figure 14e) and stovetops Figure 14f). Electricity is by far the most popular form of energy, which confirms HEEP's data that electricity accounts for 69% of household fuel type.

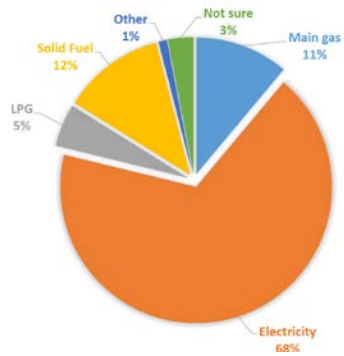


Figure 14a: Q11.1- Heating Fuel

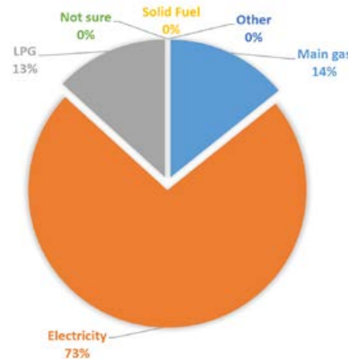


Figure 14b: Q11.3- Stovetop Fuel

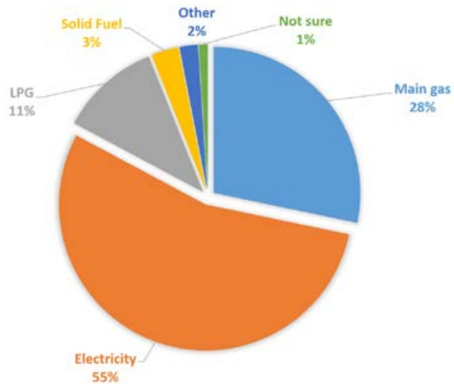


Figure 14c: Q11.2- Water Heating

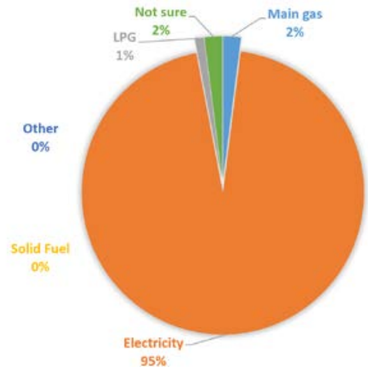


Figure 14d: 11.4- Oven Fuel

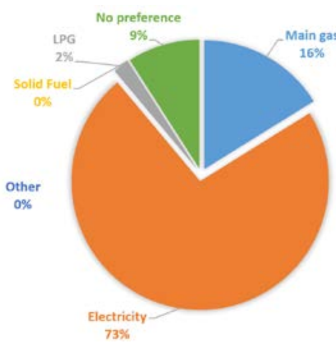


Figure 14e: Q12.1- Oven Fuel Preference

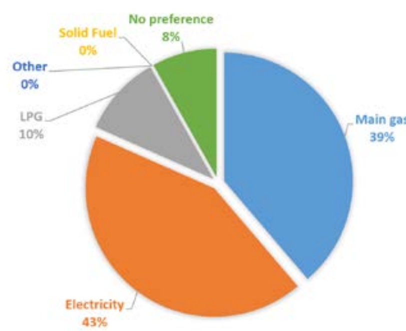


Figure 14f: Q12.2- Hob Fuel Preference

Figure 14: Home Appliance Fuel Information and Preferences (n = 99)

Our data appear comparable to the HEEP data for all domestic energy, but our results are rather high for electricity use in heating homes. The average fuel-source for heating, cooking, as well as the preference method of cooking was electric. Main gas came second each time except for heating the home, which was almost equivalent to solid fuel. Gas is the consistently second most popular fuel for cooking.

The data below best translates to the reliability standard that the HyLink™ has to meet in order to keep its users happy (see Figure 15). In other words, since there is no system that can be one hundred percent reliable, and there are days where weather conditions might not allow for the system to produce hydrogen how long would user's be willing to sustain regular life without access to hot water, or in turn, how large should the fuel storage be?

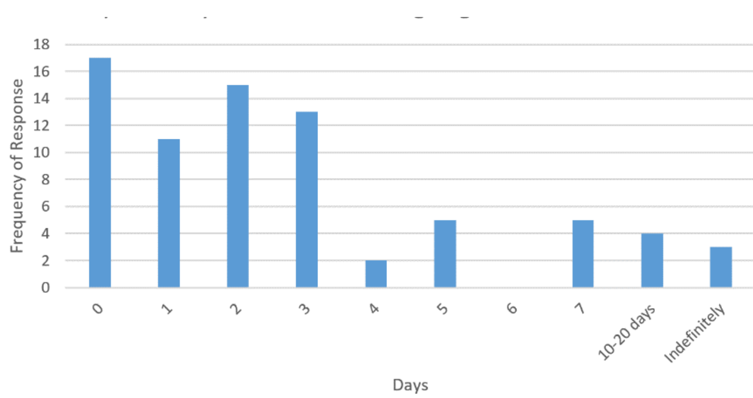


Figure 15: Time before Hot Water is Necessary (n = 76)

4.4 Objective 4. Assess the current TRL of the HyLink™ system

In this section we discuss results of our implementation of the TRLA for TRL 7 and 8.

4.4.1 TRL 7 Assessment

According to the data gathered from parsing the HyLink™'s log files over the last year (February 2nd - December 29th 2016), we were able to calculate the average rate at which the current pilot HyLink™ installation produces H_2 gas. We found this rate to be approximately 0.0579 kg of H_2/Hour. HEEP Data regarding household energy use combined with the number of occupied residencies from the 2006 census (the data was collected in 2007), we were able to calculate that the average house requires 20,481.80 Megajoules (MJ) of energy per year for water heating and appliances. According to HEEP, the total amount of energy consumption is 11,410 kWh or 41,076 MJ, which corroborates the total energy usage from the data. It is important here to note that by including all appliances from this dataset, we are overestimating the energy demand because the figure includes more than heating and cooking and appliances such as computers and entertainment systems. Since the energy density of gaseous H_2 is 119.88 Megajoules per kilogram we were able to convert that figure into kilograms of hydrogen. The HyLink™ system in its current state could theoretically produce enough hydrogen to fulfill a typical household's thermal energy needs.The data we gathered from our public survey is important as well because it shows typical household energy behavior, perception, and preferences.

Table 2 (below) is a table of the TRL 7 questions that were in the final implementation along with their answers.

Table 2: Table Comprehensive TRL 7 Guidelines

TRL Question	**Success and Qualification**
Is the system fully autonomous in operation?	Yes
How many days of resilience does the HyLink™ system offer for an average New Zealand home?	1.41
What size tank would be required for a week's resilience (without economization)?	~11,000 L
What is the overall efficiency of the system?	68-75%
Does HyLink™ produce enough hydrogen to meet an average New Zealand household's average thermal energy needs?	Yes

One example of this is that we asked respondents with household appliances (e.g. dryer, washing machine, dish washer) whether they had an economy mode and, if so, do they use it (see Figure 16).

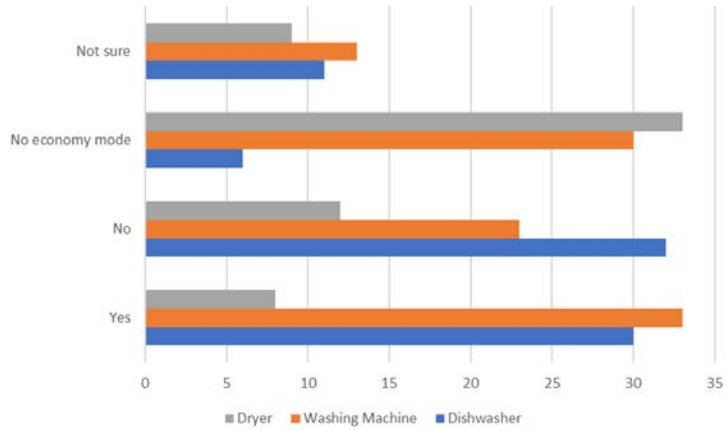


Figure 16: Use of Economy Mode on Household Appliances

(n_{Dryer} = 62, $n_{WashingMachine}$ = 99, $n_{Dishwasher}$ = 79)

This data suggests a willingness for respondents to watch and mitigate their resource consumption, which is beneficial to the early adoption of the system.

HyLink™ is designed to run autonomously, switching the electrolyser on when there is enough power available from the solar arrays or wind turbines and when the storage tank is operating below maximum capacity. The reliability and stability of this software controller is paramount because according to our public survey, the average time people are willing to go without hot water is roughly 2 days. The HyLink™ installation on Matiu/Somes has been running autonomously for nearly 3 years, and the MIH installation has successfully ran autonomously in the past but is currently undergoing experimentation. This shows the resilience of the software, and its ability to recover from possible mechanical faults. If the software remains so reliable and the system continues to produce hydrogen at its average rate, HyLink™ qualifies for TRL 7 and should be advanced accordingly. To see specific TRL 7 questions please see Appendix A.

4.4.2 TRL 8 Assessment

According to the data collected from our user surveys as well as our public survey, we were able to determine how fit-for-purpose HyLink™ is and how usable the system is in a "real life situation." The user experience surveys provided answers to whether HyLink™ provides useful services to its users. It must be noted, however, that since the appliances used in conjunction with HyLink™ are less mature in terms of development, even the user experience responses have a form of bias. A general overview of the TRL 8 guidelines can be seen below in Figure 17.

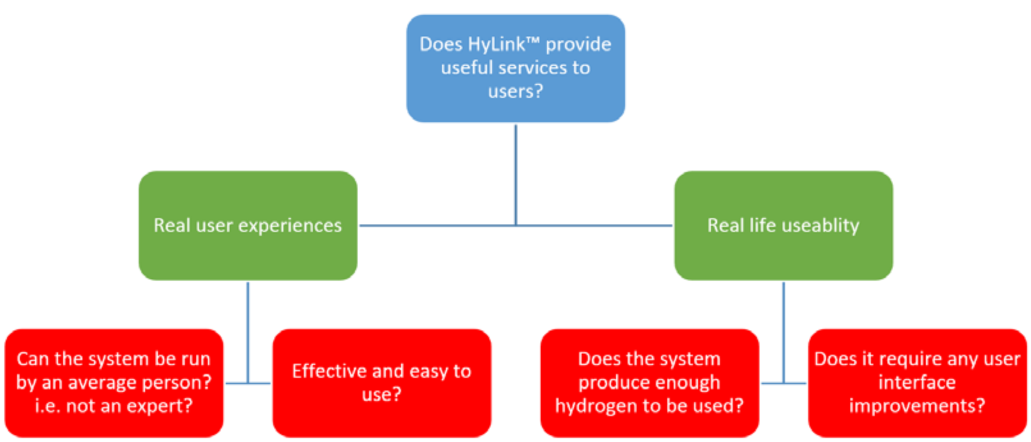


Figure 17: Criteria for TRL 8

A more thorough framework of the TRL 8 guidelines can be seen below in Table 3. We used our user survey data to assess HyLink™ in three main categories: "How well do the appliances work?" (Simplicity, ease of use, effectiveness/similarity to typical household appliances), "Are the appliances easy to use?" (Can the appliances be operated with minimal training or instruction), and "Do the users perceive the system as fully functioning and usable."

Table 3: Comprehensive TRL 8 Guidelines

TRL Question	Success and Qualification
Do the appliances work well? (Simplicity, Ease of use, effectiveness/similarity to typical household appliances)	Yes[1]
How long does it take for hot water to come?	Range: 5-30 seconds, Average: Less than 15 seconds (10 seconds), Median: 15 seconds.
Is the amount of hot water produced sufficient?	Yes; 76% of users were extremely satisfied.
Is the amount of hot water produced enough for an average household on a daily basis?	Yes[2]
Are the user experiences positive?	Yes[3]
Are there major differences in taste/speed when cooking via hydrogen gas vs electric/gas?	Yes[4]
Did you lose hot water at any time during use?	No
Did the hot water lose heat during use?	Yes[5]
Did the hob, grill, or smoker stop working during use?	Yes[6]
Did the hob, grill, or smoker lose effectiveness over the duration of use?	No
Are there differences in usability in comparison to systems users are used to?	Yes[7]
Are the appliances easy to use? (Can the appliances be operated with minimal training or instruction)	Yes[8]
Do users perceive the system as fully functioning and usable?	No[9]

Key responses that affected TRLA:

Additional comments received in the user survey are used below to help prove/qualify the outcomes of the success criteria above. The numbers associated with the Yes or No answers in the table above denote the explanation of the answer given below.

1. **Do the appliances work well? (Simplicity, Ease of use, effectiveness/similarity to typical household appliances)**
    a. **In general**

    Positive: “It seems like a system with a lot of potential, appears to work well.” “Overall it was really neat to see a hydrogen fuel/electrolysis based system. Awesome to see the progress being made to get off traditional fossil fuels, and the grid.”

    b. **Water heater**

    Positive: “The hot water system appeared to function as well as a traditional gas or electric powered boiler would.

    “Worked well didn't really notice any major differences between a regular sink. Water was hotter than usual.”

    Negative: “The water issue was confusing, I'm not sure why it suddenly ran cold and did not heat back up - perhaps it needs more time to recharge?”

    “Just a comment, my data might be a little skewed because I used the hot water directly after some others used it.”

    Explanation: If the user in our observation used the hot water system in any way immediately following another user two scenarios may occur: 1) There is immediately hot water, which is still left over in the piping system even if the hot water heater is not running, 2) There is no hot water because there has to be a demand for hot water of roughly 10 seconds before the instant water heater begins to produce hot water again. If dissatisfied users attempted for less than that time, their perception may be “No” the hot water heater did not work well. The majority of users’ external comments did not experience a lack of hot water, and found no difference between HyLink™ in comparison to traditional appliances.

c. **Barbecue**

Positive: “Food cooked well, but it seemed at max capacity.”

Negative: “The grill is slow to cook food.”

“The right side of the barbecue did not work and the grill didn't get as hot as propane grills. The knobs to control the temperature of the grill were a bit confusing as you can turn them each multiple times.”

Explanation: The hydrogen flow needs to be increased to allow the grill to burn hotter. Originally this value was set to 75 kpa when the appliance was used with the HyLink prototype system on the Matiu/Somes island but it is currently being tested at 3 kPa; a difference of almost 25 fold. The right half of the barbecue was never updated and contains no burners, so if any users attempted to use this side of the appliance they would have perceived a lack of heat. The knobs on the barbecue need to be updated because they are currently connected to a needle valve and in order to ensure adequate hydrogen flow the knobs turn in either direction multiple times making it ambiguous what temperature setting the barbecue is on.

d. **Cooking hob**

Positive: “It boiled the water incredibly fast but maintained enough temperature control to not overdo it.”

Negative: “The small burner extinguished during use.”

Explanation: Similarly to the barbecue, the flow of hydrogen to the burner itself is too low and needs to be increased in order to be sustainably lit. It is also important to note the windy conditions during the testing and that in a real-life application this appliance would be inside and not have to sustain constant wind.

2. **Is the amount of hot water produced enough for an average household on a daily basis?**

Tests show that the current 2200 Liter hydrogen storage tank (at a pressure of 3.5 barg, the equivalent of 22 kWh (80 MJ)) is sufficient to sustain a continuous shower 55 minutes. According to the respondents of our public survey, the average household shower length of New Zealand citizens is between 6-10 minutes. The survey results also show that a typical household shower is run 4 times a day; on average. Combining these two statistics results in 24 to 40 minutes of shower time on average in a typical New Zealand home. Both the low and high end estimate are less than the maximum shower time of the MIH implementation of the HyLink™ system. Additionally, based upon the TRL 7 data, the storage system is sufficient enough to meet the household's entire thermal energy demand for over a day and therefore capable of handling daily shower loads.

3. **Are the user experiences positive?**

   Positive: "Overall it was really neat to see a hydrogen fuel/electrolysis based system. Awesome to see the progress being made to get off traditional fossil fuels, and the grid."

   "The hot water system appeared to function as well as a traditional gas or electric powered boiler would."

   Negative: "It seems like a system with a lot of potential, appears to work well."

   "Seems to just be the design of the plumbing that resulted in the longer heat up times and pressure differences."

   Explanation: The negative responses received were based upon lack of hot water, and potential differences in taste. Both of these are simply explained, and were not consistent responses amongst the majority of users. Often responses were actually an analysis of their observation, which is perception, but a comparison to traditional household systems would have been more desirable. For example, responses claimed that plumbing was the primary reason for any fluctuation in water temperature and pressure, and thus does not directly reflect the performance of the HyLink™ electrolyser or hot water system. We also do not believe that taste is not as valid of a criteria in our assessment since we did not have a blind side-by-side comparison, but rather responses were based upon memory.

4. **Are there major differences in taste/speed when cooking via hydrogen gas vs electric/gas? (barbecue needs more design before fit for market)**

   Positive: "Food cooked well, but it seemed at max capacity."

   Negative: "The hydrogen powered grill did not reach high temperatures like a propane or charcoal grill would."

"The knobs to control the temperature of the grill were a bit confusing as you can turn them each multiple times."

Explanation: As mentioned earlier (see Key Response 1), the flow of hydrogen must be increased to adequately compare with a typical electric/gas system. The temperature controls are simply adjustable and the hydrogen valve's threshold within the appliance can be adjusted to better suit the user's needs.

5. **Did the hot water lose heat during use?**

   Explanation: If a user used the hot water appliances too quickly after another user there may already be hot water in the pipe although the instant water heater is temporarily off between uses. In this case the amount of hot water remaining may be limited, followed by a period of cold water. We wanted to prevent influencing user's responses by suggesting this difference in the system in comparison to a traditional water heating system. This is the phase where the instant water heater recognizes there is a necessity to start up again to produce hot water. If users did not wait long enough for these phases to occur they may have negatively perceived their experience with HyLink™. An instance where the instant hot water heater is incapable of producing hot water due to a lack of hydrogen has not yet ever occurred, and there was excess hydrogen available (ready to use to produce hot water) during the timeframe where participants tested the system. If the storage had been empty then their observation would have been legitimate. Previously user experience data from consistent users of the water basin and shower on a day to day basis found no consistency that hot water ever ran out.

6. **Did the hob, grill, or smoker stop working during use?**

   Explanation: The only appliance that stopped working during use is the small burner on the hob. Additionally, the setting that controls the overall flow of hydrogen can be increased to suit the user. The hydrogen flow for the small burner was too low to sustain the flame under breezy conditions on the day of observation and thus with a higher under a stronger flame this result may not occur. The barbecue's hydrogen flow also needs to be resolved and updated (See Key response 3).

7. **Are there differences in usability of the water heater in comparison to systems users are used to?**

   Positive: "The hot water system appeared to function as well as a traditional gas or electric powered boiler would."

   Negative: "The sink changed the water pressure in the shower quite drastically and the shower water pressure dropped when it went from cold to hot."

   Explanation: The HyLink™'s water heater is instant, the observations and notes from the users encompass the issues with all current-generation instant hot water heaters. The time it takes for a hot water heater to deliver hot water is much more reliant on the length of pipe between the heater and the faucet than the fuel the system uses. The issue regarding the drop in water pressure stems from the temperature of the water heater being set too low and can be changed on the machine itself.

8. **Are the appliances easy to use? (Can the appliances be operated with minimal training or instruction)**

   Explanation: All users had no prior training, and we found that user of all appliances found their experience to be very straightforward. The largest issue noticed was with the knobs to control the temperature of the barbecue. The system was built with needle valves for more precise control but it means they must be rotated more than once for large differences in temperature. This results in the knobs being left fully open and the main valve connecting the barbecue to the regulator being used to turn the appliance on or off. This may also cause ambiguity as to what temperature setting the barbecue currently exists in.

9. **Do users perceive the system as fully functioning and usable?**

   Positive: "Worked well didn't really notice any major differences"

   Negative: "Limited use [of the system], would be interested to see how it works in colder weather"

   Explanation: The overall system's functionality could have been better communicated to users of the system to realize how it actually works, and differences that might result because of this. This is not necessarily negative because it provided no prior bias to the user's via guidance. We recommend a larger sample size, and a revised set of questions made with slight adjustments to the appliances so that the user's interpretation of the appliances more realistically correlate to the maturity of the HyLink™ system itself.

From these data we have determined that the HyLink™ system in its current standing may not quite meet the requirements to be classified as TRL 8. The majority of the system, however, including the electrolyser, the storage tank, the size of the storage tank, and the renewable energy systems (PV, turbines) do meet the requirements for TRL 8. This translates to the actual HyLink™ system meeting TRL 8, but some of the proof of concept appliances which show the potential to function need to be further refined.

Part 2. Discussion

An interesting statistic found from our survey data is that electricity was used as a fuel source by a majority of respondents for every thermal appliance. However, the data collected for one's "preferred fuel for hob" stands out because the difference between electricity and gas was much smaller. For this question, 43% of users prefer electricity while 39% prefer gas. A few of the survey respondents commented that they preferred gas hobs because they believe that the heat is easier to control, and that it provides a more even spread of heat. These end-user preferences allow for a demand for gas powered hobs to persist even though New Zealand is moving away from non-renewable fuel sources in general. A renewable solution to this demand resides in the HyLink™ system, as hydrogen powered cooking appliances also burn hydrogen directly, therefore performing similarly to natural gas based appliances.

The data gathered from the user-experience survey contains a few inconsistencies in certain questions. In the data, there is a large discrepancy in the responses to the question "How long did the water take to heat up?" The answers ranged between 5 seconds and 20 seconds with almost equal amounts of responses for both ends of the spectrum. One possible factor involved in this gap is an individual's perception of time. All the given responses to the question were within 15 seconds of each other, and without a definite way for the participants to measure time, the responses relied on the participants' perception of time. This can affect the results of this question because, for example, what a user perceives to be 15 seconds may actually be 5 seconds. A more precise way to answer this question would be to time the hot water with a stopwatch several times to find a consistent average. However, a more precise statistic is not required because a majority of the users' experiences related to the hot water appliances were positive regardless of the exact startup time of the hot water.

Another important point to note regarding the reliability of the user experience data is that the data was gathered during a specialized test of the system, and not under normal operating circumstances. During our specific test, 19 users tested the hot water appliances within a short amount of time. A typical household, according to our survey data, would only have an average of 4 people using the hot water appliances over the course of the day. This allows for certain anomalies with the hot water system described in the users' comments to be analyzed and subsequently discounted as they do not reflect typical circumstances.

Having used the TRLA to examine the progress of the HyLink™ system, we find it beneficial to analyze the usefulness of the TRLA itself. From our experience, the TRLA is very useful in classifying the technological development of a project in discrete stages. For example, if one describes a technology as being "about TRL 4", it is intuitively taken to mean that the technology is in the prototype stages of development, and is still being designed. In situations where everyone is familiar with the TRLA scale, this becomes a very effective method to communicate the state of a technology. However, one significant drawback of using the TRLA is that the later stages, specifically levels 7-9, analyze certain subjective aspects of technologies. While analyzing the user experiences of the HyLink™ system, since users were asked to compare the appliances to their typical appliances at home. Consequently, their responses were subjective as they likely already have preconceived ideas of how their own appliances work, and how the HyLink™ system therefore should work. Another disadvantage in using the TRLA is that creating adequate criteria for the later stages of a technology is difficult. The criteria must encompass every aspect of a technology to ensure that it is rated at the correct TRL. We believe that when considering the development of a technology, it would be helpful to carefully consider the metric used to perform the analysis. TRLA may be sufficient for some simpler technologies, but other, more technically complex technologies may benefit from an analysis from a different metric, or even a combination of TRLA and another metric.

5.0 Recommendations and Conclusions

The HyLink™ system, in its current standing, is nearly at TRL 8 and it can be argued that it is already there with the caveat that some of the appliances need to be adjusted. Our own findings revealed some recommendations that we would like to propose for the HyLink™ system, ordered by complexity and cost from easiest to hardest.

1. **Heat warnings.** Hydrogen is a colorless, odorless gas, and emits no visible light when combusted; making it much harder to tell when HyLink™'s cooking appliances are on. The inclusion of a heat warning might mitigate concerns as a selling point to early adopters who may be skeptical about the safety of the system. The current temperature-indicating labels may not be adequate for long-term use, as their operational limits are roughly 90 degrees Celsius. We recommend auxiliary safety warning, similar to that of traditional cooking appliances. This safety warning could be much simpler than it currently is by just including a red LED that indicates whether the stove is hot or not.
2. **Hydrogen flow to the appliances.** One of the most common negative responses we received in our user survey is not specifically a problem with the HyLink™ system itself, but rather that the cooking speed of the appliances was too slow. With an increase to the flow of hydrogen to both the hob and the barbecue, the small burner of the hob is likely to stay lit, and the barbecue is likely to get hotter and consequently cook food faster.
3. **Software updates, bug fixes, & end user app.** The current software itself has proven to be quite resilient but remaining vigilant for bugs and inexplicable software behaviors should remain near the top of the priority list. A mobile app for an end user has the potential to be a major selling point for the HyLink™ System. With the advent of the connected home and smart appliances, it is possible to port data from the system and enable it to work in unison with devices like smart thermostats and smart washing machines. Even further down the road, if the system were to become commonplace, there is potential to add a social component similar to electrical companies in the United States comparing your energy usage to the usage of your neighbors. In addition to data visualizations, there is also the ability to add safety warnings to notify the user if anything were to go wrong with the system. Below is a sample mockup of what the companion app could look like when connected to the HyLink™ System.

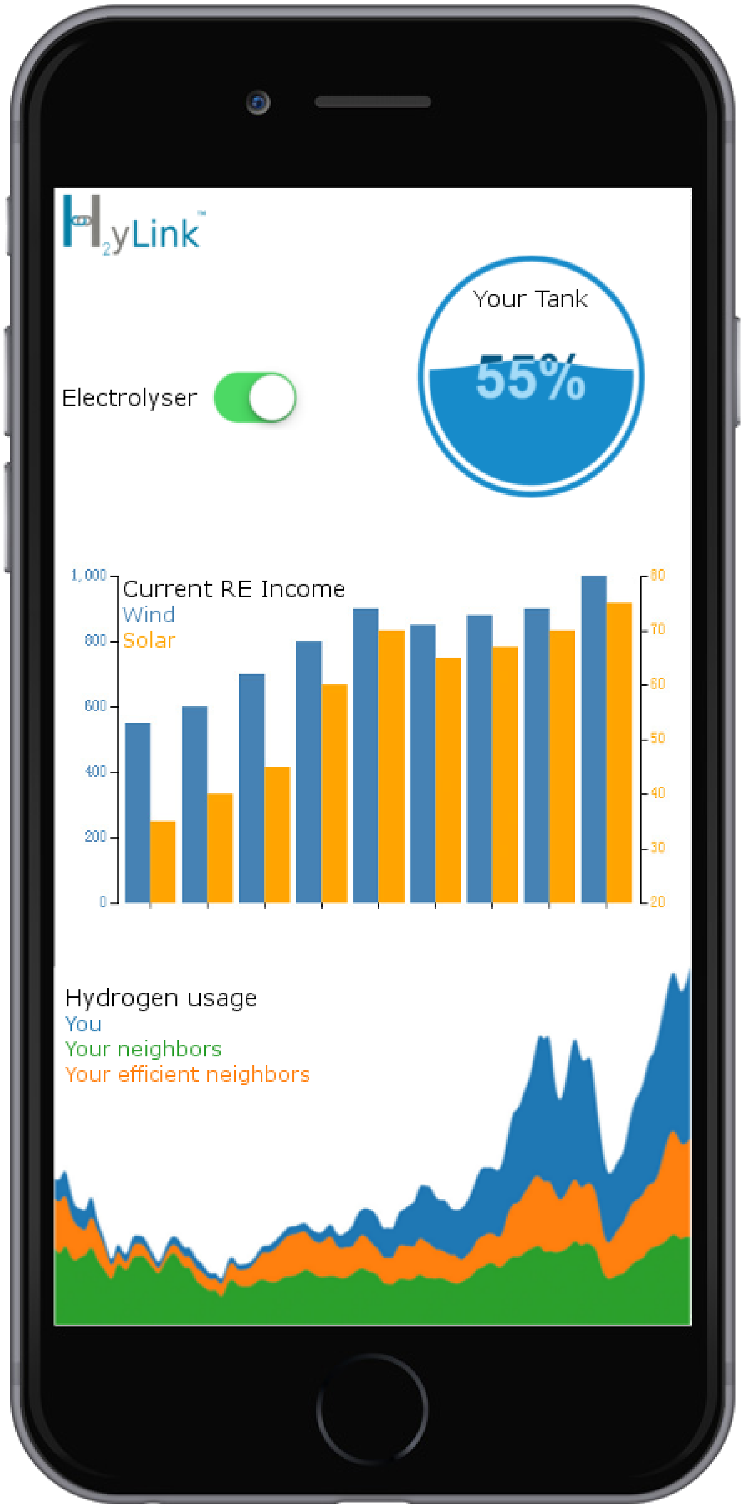


Figure 18: HyLinkTM App Mockup

Conclusion

The HyLink™ system has successfully surpassed TRL 6, and we recommend that HyLink™ should be placed above TRL 7 but below TRL 8. By compiling the system's log files that were produced over the past year we were able to model the HyLink™ system's average production of hydrogen and gauge its resilience. This information was combined with data gathered from our public survey of 99 participants regarding average household energy use to see if we could conclude beyond reasonable doubt that HyLink™ could meet the energy demand for an average household of four. Our public survey data was corroborated with publically available data from the New Zealand government to ensure consistency and integrity of our results. Based upon this evaluation we placed HyLink™ above TRL 7. We believe HyLink™ is near to fulfilling TRL 8, and we have noted a few suggestions in our recommendations that, if addressed, will push HyLink™ past TRL 8.

We are glad to have been a part of such an amazing opportunity to help further develop a cutting-edge renewable energy system. Hydrogen energy has great potential in replacing nonrenewable energy sources in the residential sector, as HyLink™ demonstrates, as well as on a greater scale, such as fuel sources for vehicles. Innovation in renewable energy is critical for the large-scale reduction of carbon emissions. Successful new technologies, like HyLink™, encourage further innovation, and can lead to a substantial shift in attitudes toward sustainable energy on a national, and eventually an international scale.

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Appendices

Appendix A: Comprehensive criteria for TRL 7

TRL Question	Success and Qualification
Is the system fully autonomous in operation?	Yes
How many days of resilience does the HyLink™ system offer for an average New Zealand home?	1.41
What size tank would be required for a week's resilience (without economization)?	~11,000 L
What is the overall efficiency of the system?	68-75%
Does HyLink™ produce enough hydrogen to meet an average New Zealand household's average thermal energy needs?	Yes

Appendix B: Comprehensive criteria for TRL 8

TRL Question	Success and Qualification
Do the appliances work well? (Simplicity, Ease of use, effectiveness/similarity to typical household appliances)	Yes[1]
How long does it take for hot water to come?	Range: 5-30 seconds, Average: Less than 15 seconds (10 seconds), Median: 15 seconds.
Is the amount of hot water produced sufficient?	Yes; 76% of users were extremely satisfied.
Is the amount of hot water produced enough for an average household on a daily basis?	Yes[2]
Are the user experiences positive?	Yes[3]
Are there major differences in taste/speed when cooking via hydrogen gas vs electric/gas?	Yes[4]
Did you lose hot water at any time during use?	No
Did the hot water lose heat during use?	Yes[5]
Did the hob, grill, or smoker stop working during use?	Yes[6]
Did the hob, grill, or smoker lose effectiveness over the duration of use?	No
Are there differences in usability in comparison to systems users are used to?	Yes[7]
Are the appliances easy to use? (Can the appliances be operated with minimal training or instruction)	Yes[8]
Do users perceive the system as fully functioning and usable?	No[9]

Appendix C: Previous HyLink™ User Survey

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HOT WATER				
The wait time to have hot water is ...				
Very quick	Quick	Good	Slow	Too slow
Comment :				
The hot water temperature is ...				
Very good	good	Normal	Bad	Very bad
Comment :				
The adjustment of temperature water is ...				
Very easy	Easy	Good	Difficult	Very difficult
Comment :				
Do you have anything else to said on the hot water?				
HEAT SPACE				
The space temperature is ...				
Very cold	Cold	Good	Hot	Very hot
Comment :				
Does something brothers you ? (Several possible answer)				
Noise	Odeur	Wind	Temperature	Other
Comment :				
Do you have anything else to said on the heat space?				
COOKING				
What's system you used ?				
BBQ	Hob small burner	Hob large burner	Both hob	Both hob and BBQ
Comment :				
The sarted system was ...				
Very easy	Easy	Good	Difficult	Very difficult
Comment :				
The cooking time was ...				
Very quick	Quick	Good	Slow	Too slow
Comment :				
The baking temperature was ...				
Very cold	Cold	Good	Hot	Very hot
Comment :				
The adjustment of temperature water was				
Very easy	Easy	Good	Difficult	Very difficult
Comment :				
Do you have anything else to said on the cooking?				
Outside system				
How do thinks of outside system ?				
Beautiful	Quiet	Inconspicuous	Good	Suitable
Ugly	Noise	Seeing	Bad	inadequate
Comment :				
Do you have anything else to said on the Ouside system?				

Appendix D: The improved survey for the HyLink™ system at the Matiu/Somes site

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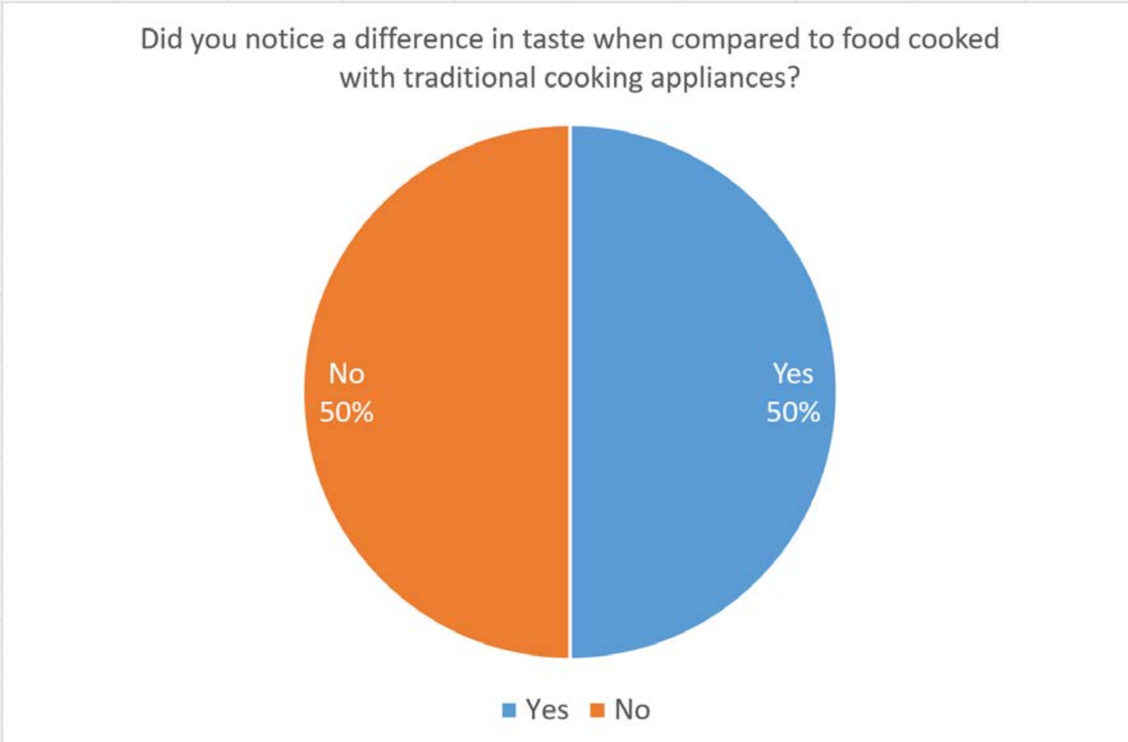
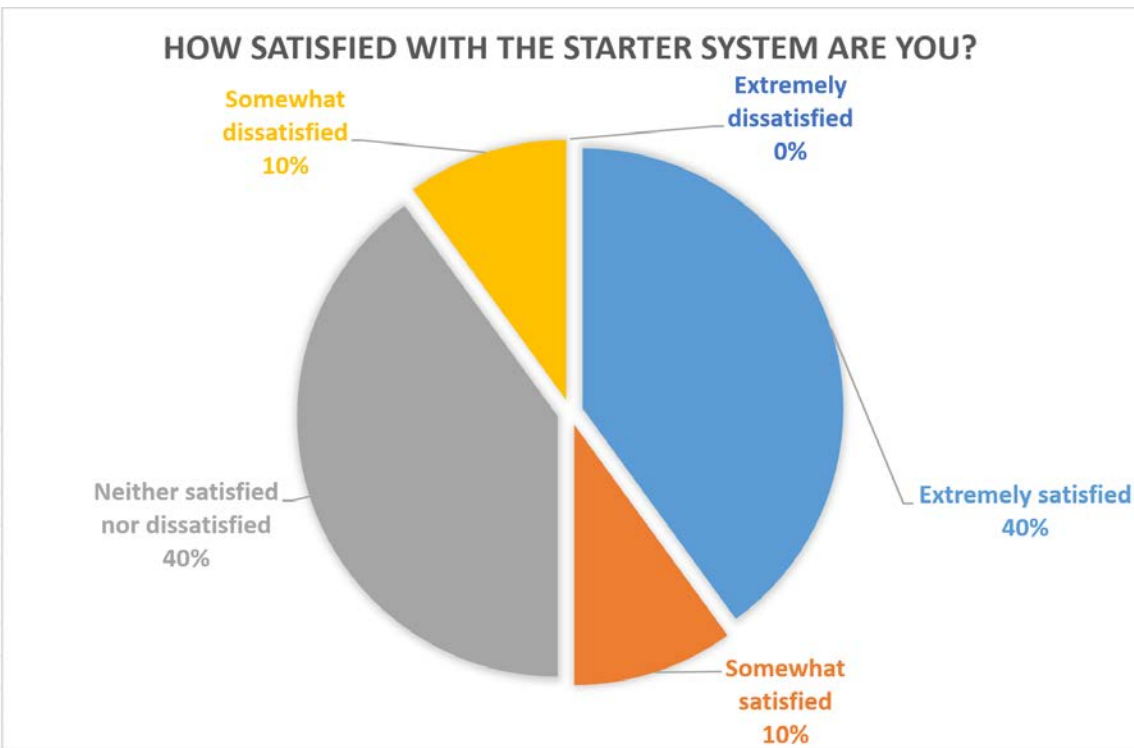
BUSINESSTECHNOLOGYSUCCESS

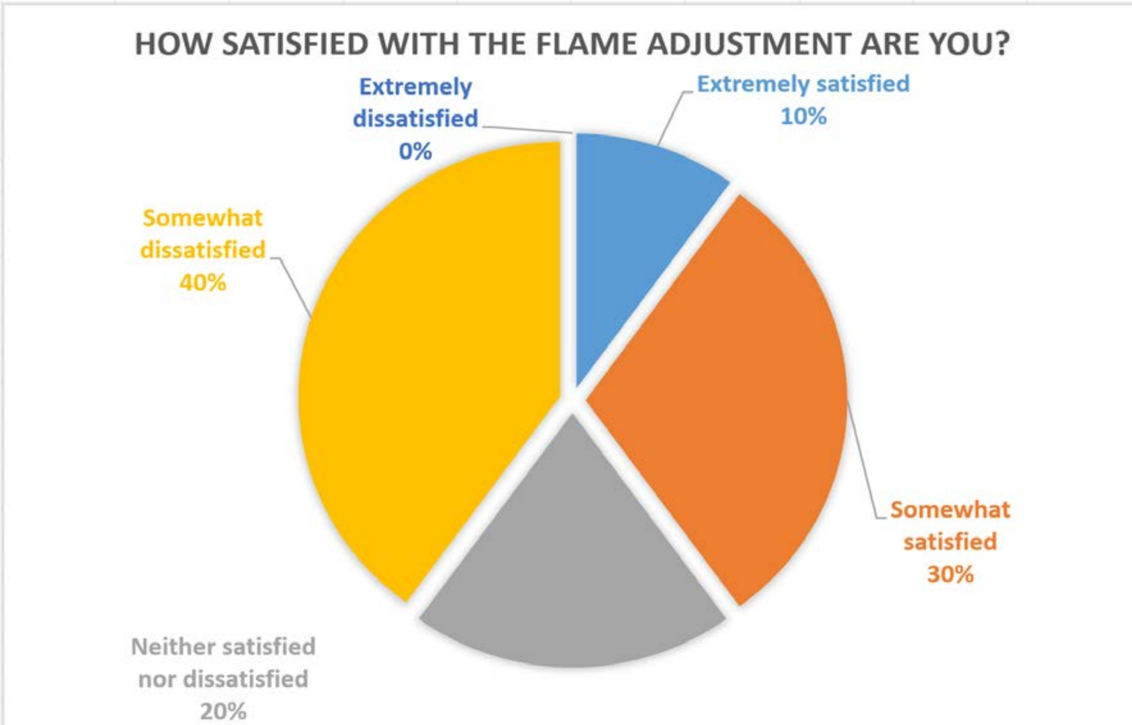
The HyLink™ system is an experimental 100% green energy system that uses hydrogen gas to suit the energy needs of an average home. The following survey is for the sole purpose of making improvements on the HyLink™ system as a whole. All information gathered is completely anonymous. For more information on the system, please visit www.hylink.co.nz or scan the QR code at the bottom of the page.

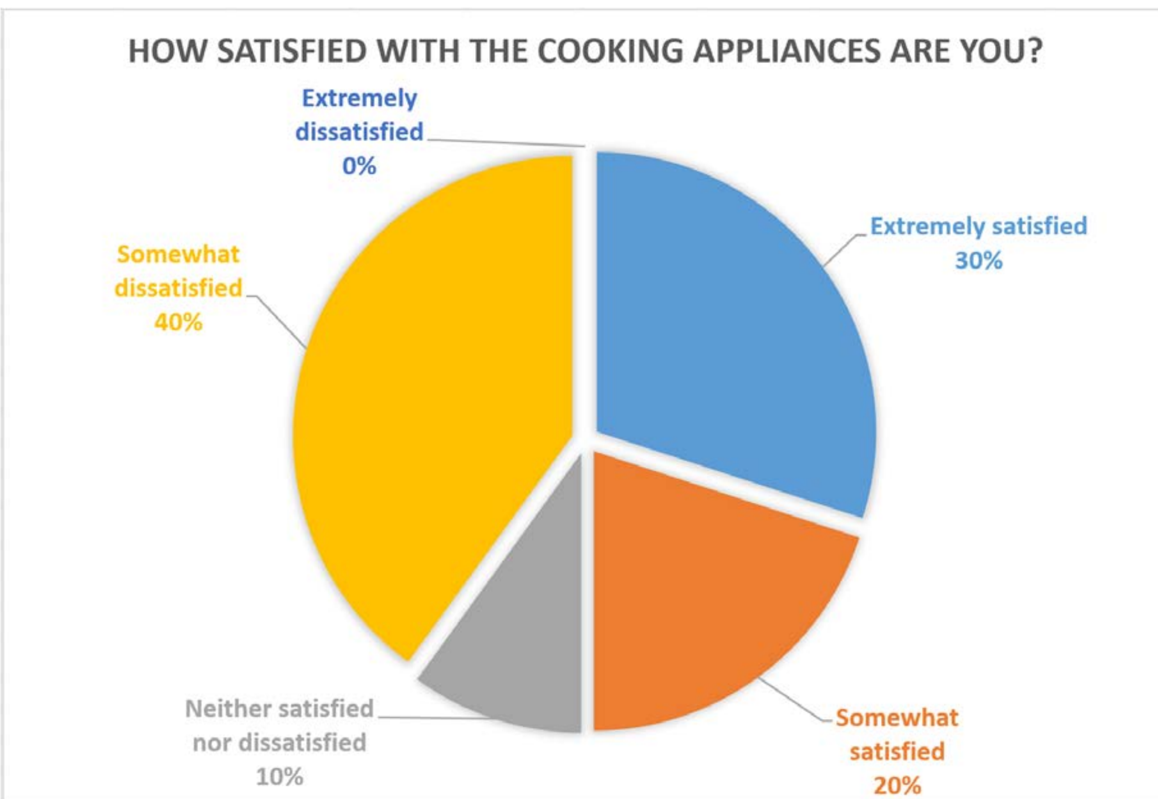
Hot Water				
Which hot water appliances were used?				
Sink	Shower	**	**	**
How long was your wait for hot water?				
> 60 seconds	~ 45 seconds	~ 30 seconds	~ 15 seconds	< 10 seconds
How satisfied with the temperature of the hot water are you?				
Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied
Do you have any comments on the hot water system? If dissatisfied, why?				
Climate Control				
How satisfied with the temperature of the indoor space?				
Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very satisfied
Do you have any comments on the climate control system? If dissatisfied, why?				
Cooking				
Which system was used? (circle all that apply)				
Barbeque	Small burner (HOB)	Large burner (HOB)	Smoker	**
How satisfied with the cooking system are you?				
Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied
How satisfied with the flame adjustment are you?				
Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied
How satisfied with the starter system are you?				
Very dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied
Did you notice a difference in taste when compared to food cooked with traditional cooking appliances?				
**	Yes	**	No	**
Do you have any comments on the cooking system? If dissatisfied, why?				
Further Suggestions				
Do you have any suggestions for improvements of the HyLink system at this site?				

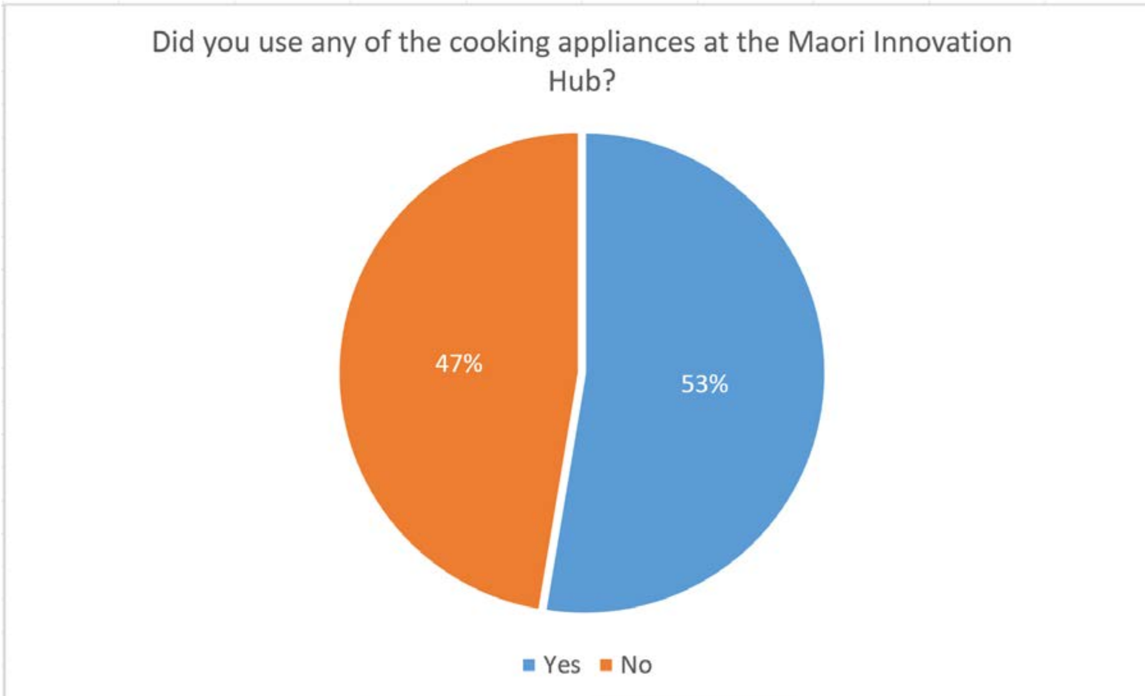
Appendix E: HyLink™ User-experience Survey Results

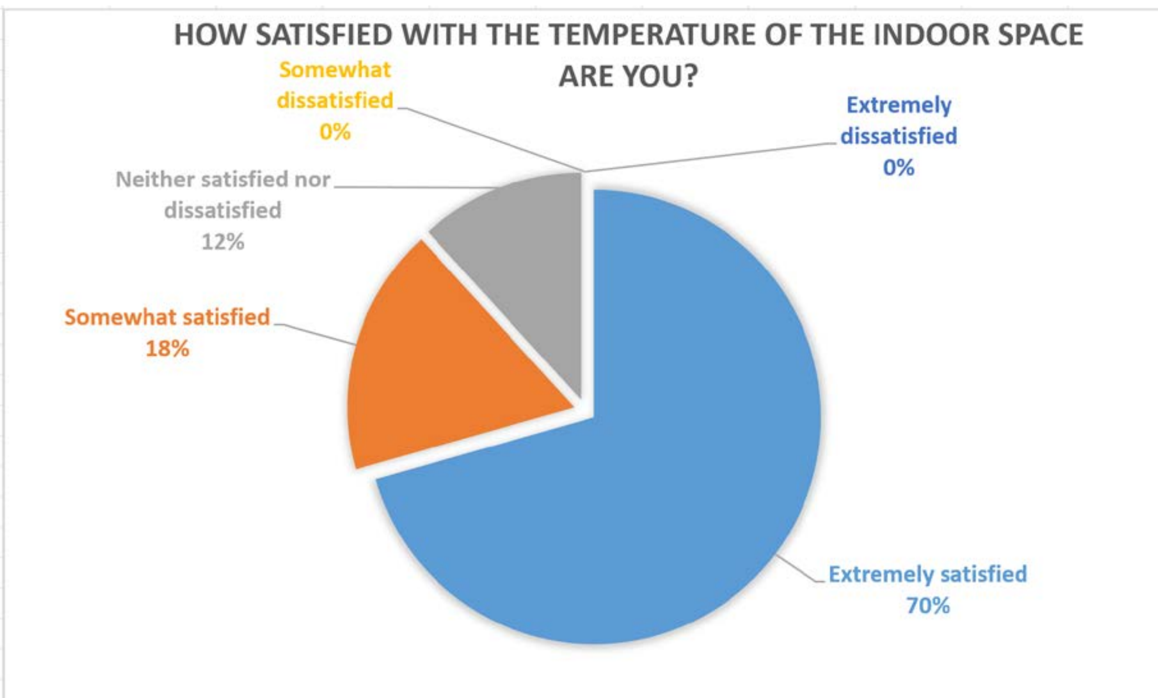




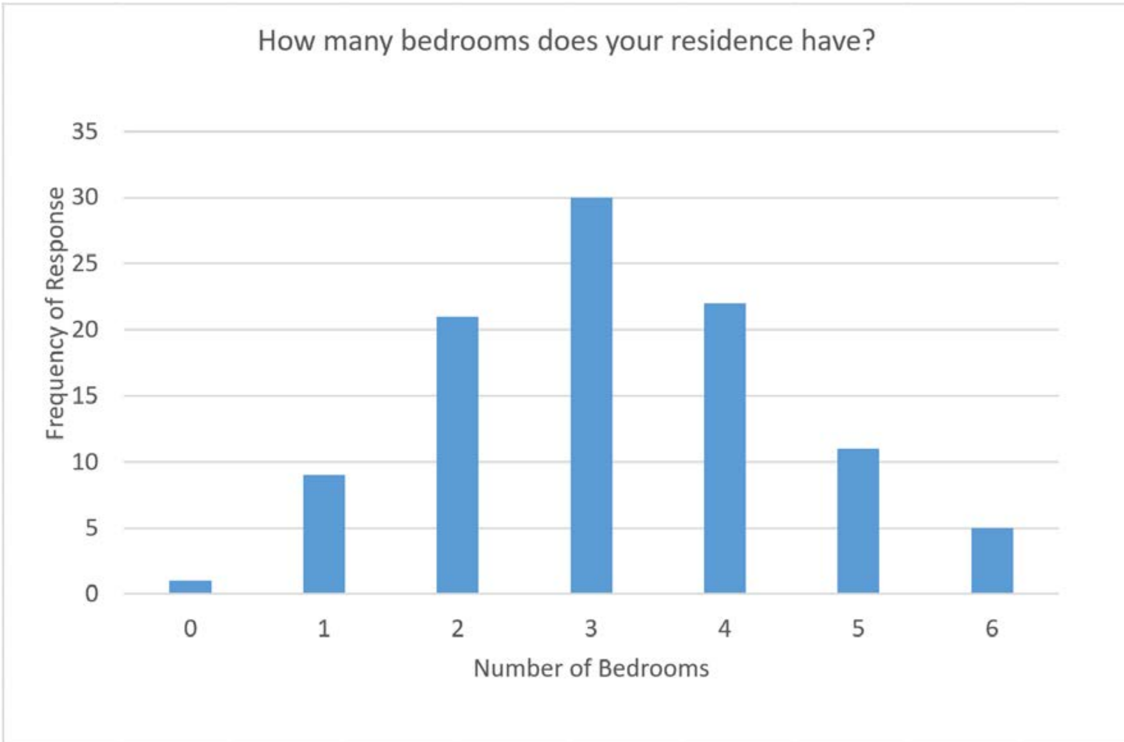

HOW SATISFIED WITH THE FLAME ADJUSTMENT ARE YOU?
Extremely dissatisfied 0%
Extremely satisfied 10%
Somewhat dissatisfied 40%
Somewhat satisfied 30%
Neither satisfied nor dissatisfied 20%

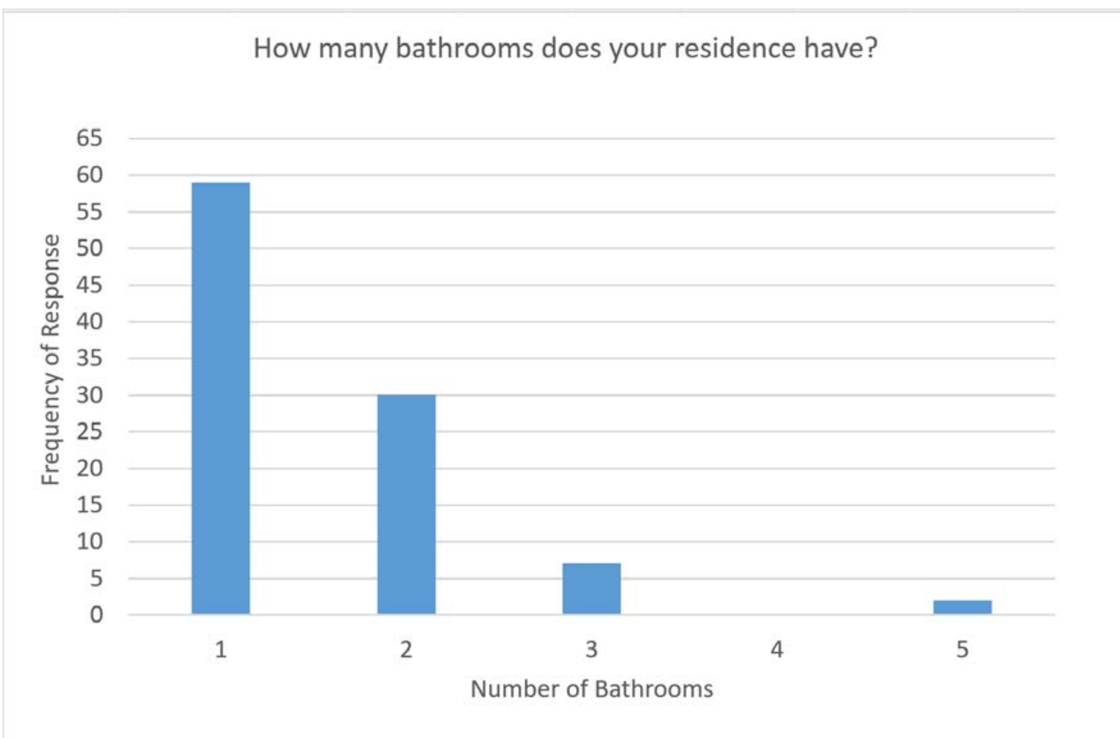

HOW SATISFIED WITH THE COOKING APPLIANCES ARE YOU?
Extremely dissatisfied 0%
Extremely satisfied 30%
Somewhat dissatisfied 40%
Neither satisfied nor dissatisfied 10%
Somewhat satisfied 20%

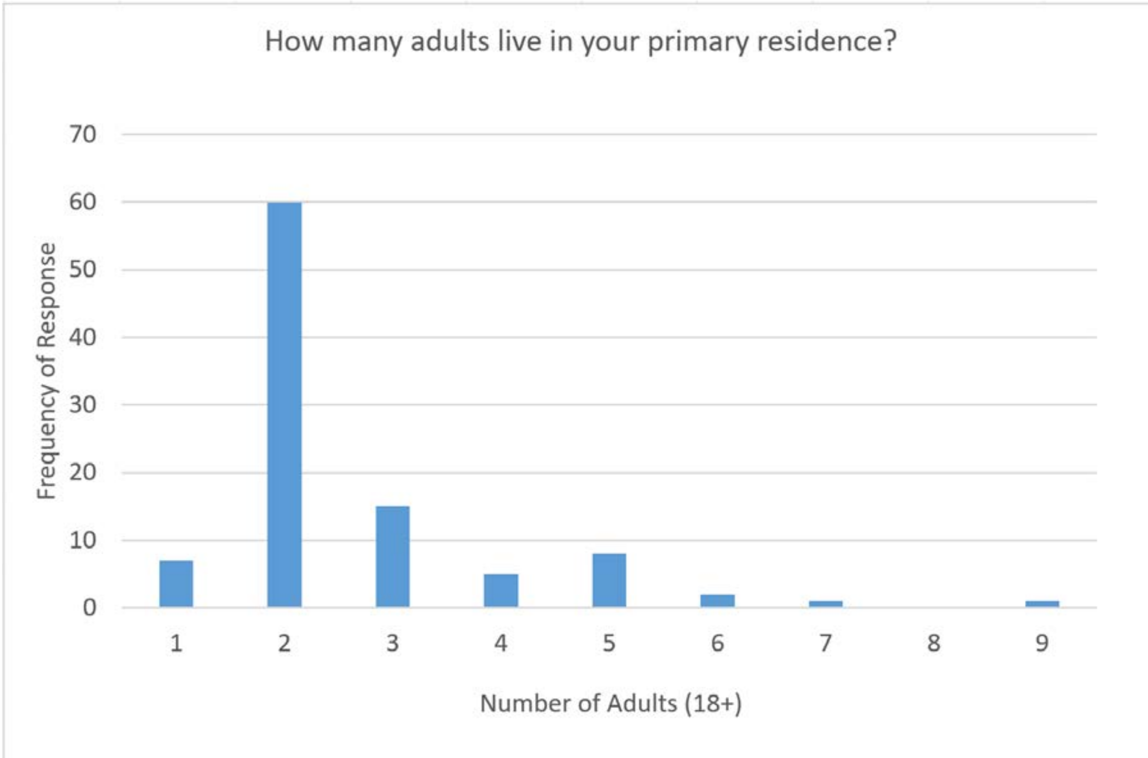

Did you use any of the cooking appliances at the Maori Innovation Hub?
47%
53%
Yes
No

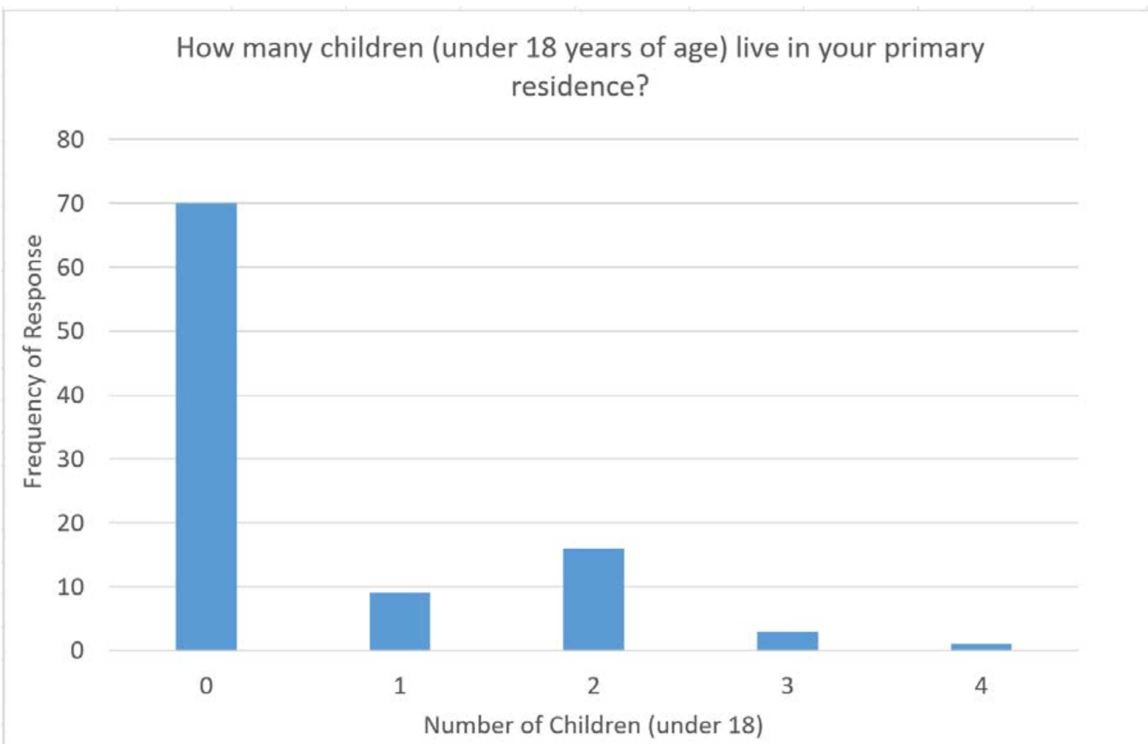

HOW SATISFIED WITH THE TEMPERATURE OF THE INDOOR SPACE ARE YOU?
Somewhat dissatisfied 0%
Extremely dissatisfied 0%
Neither satisfied nor dissatisfied 12%
Somewhat satisfied 18%
Extremely satisfied 70%

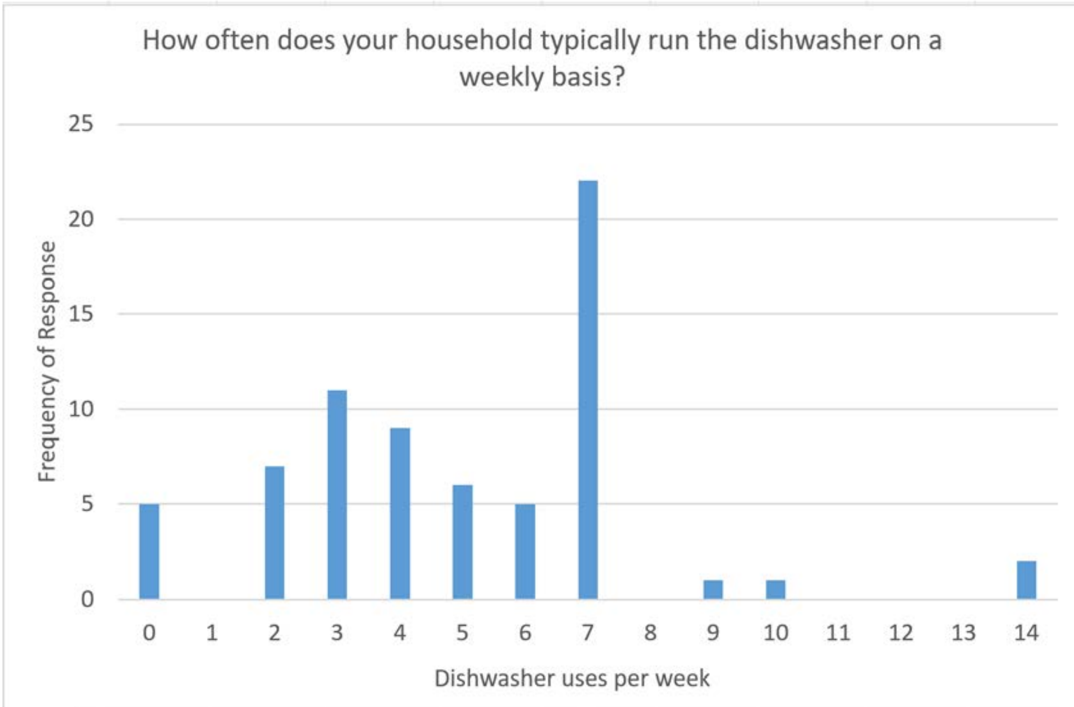
Appendix F: Public Survey Results

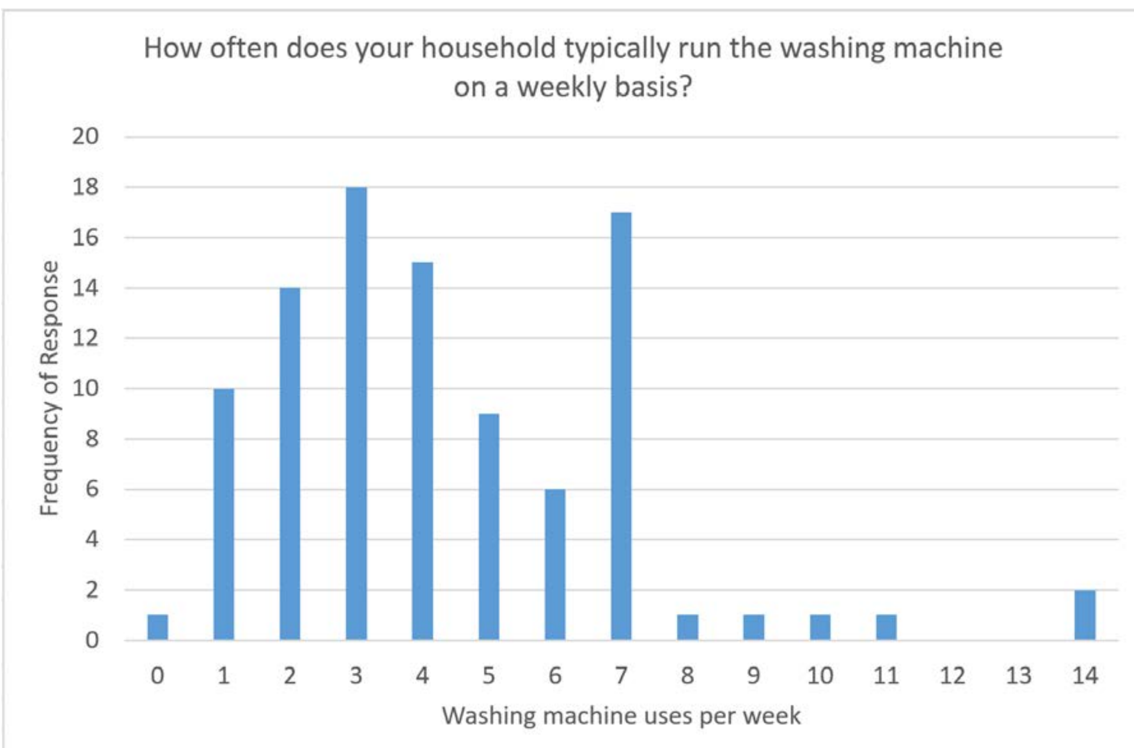


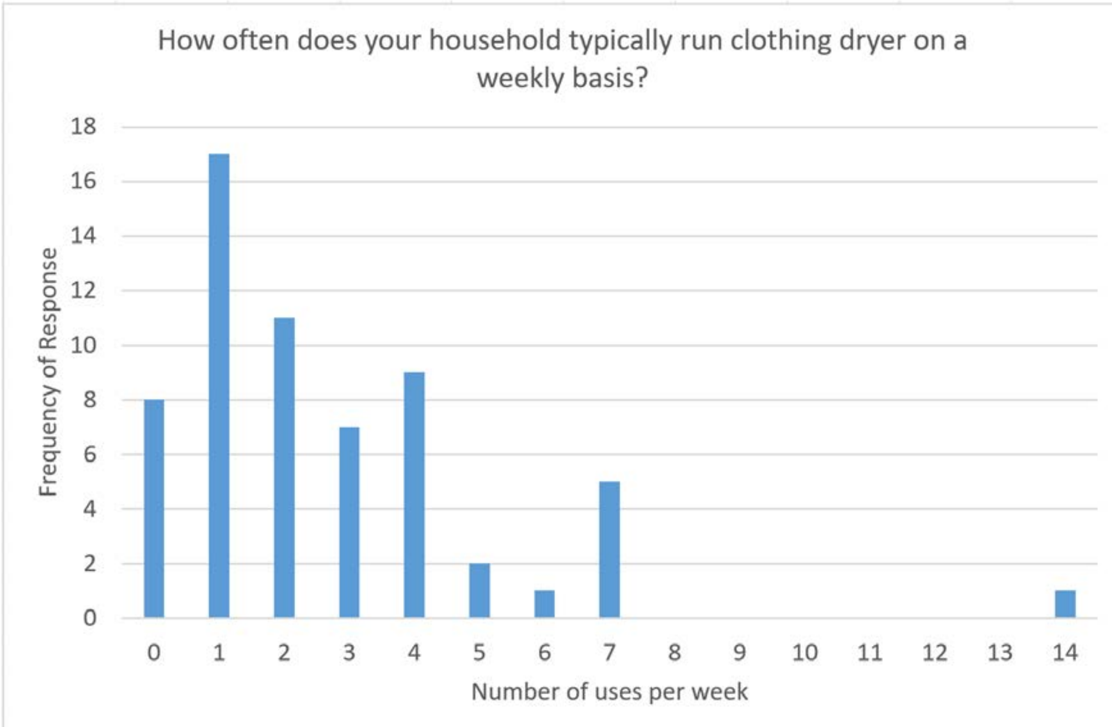


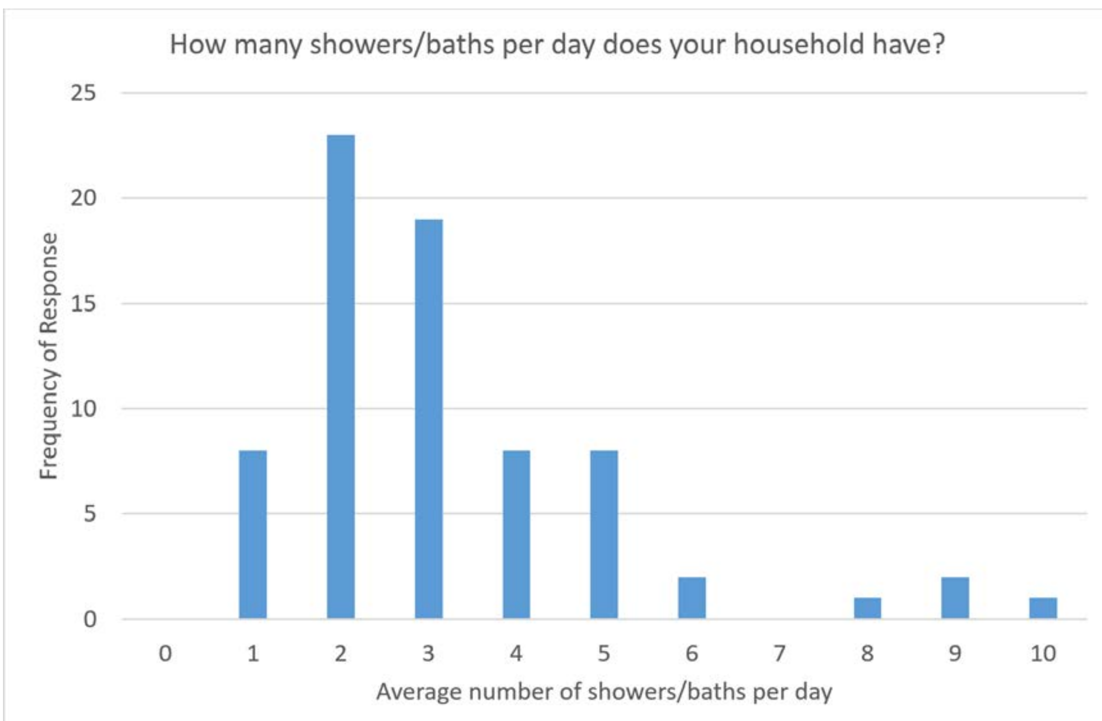

How many adults live in your primary residence?
Frequency of Response
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
Number of Adults (18+)


How many children (under 18 years of age) live in your primary residence?
Frequency of Response
80
70
60
50
40
30
20
10
0
0
1
2
3
4
Number of Children (under 18)


How often does your household typically run the dishwasher on a weekly basis?
Frequency of Response
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Dishwasher uses per week


How often does your household typically run the washing machine on a weekly basis?
Frequency of Response
20
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Washing machine uses per week


How often does your household typically run clothing dryer on a weekly basis?
Frequency of Response
18
16
14
12
10
8
6
4
2
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Number of uses per week


How many showers/baths per day does your household have?
Frequency of Response
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10
Average number of showers/baths per day