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Heat Pump Water Heaters:

Potential for Harmonization of International Test Standards

Final Report, October 2013

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Summary

The heat pump is one of the most energy efficient technologies for heating water for household use. Energy efficiency is a key point in product advertising and marketing, and important for the policymakers who manage energy labelling and minimum energy performance standards (MEPS) programs.

There are several test methods for heat pump water heaters in use in different regions of the world, with major differences between them. As a result, manufacturers have to undertake a different set of tests for each economy where they sell their products. This inhibits trade, adds to product cost and slows the development of the global heat pump water heater market.

This project analyses current energy efficiency test methods, with the aim of developing proposals for internationally-comparable methods, metrics and efficiency classes for use in future efficiency policy measures. It has been undertaken in the following stages:

1. A survey and analysis of existing test standards for heat pump water heaters;
2. Preparation of a draft Interim Report;
3. Presentation of the draft Interim Report to a Workshop of invited experts and stakeholders in Beijing, China on 12th April 2013;
4. Preparation of a draft Final Report (after comments on the Interim Report);
5. Presentation of the draft Final Report to a Workshop of invited experts and stakeholders in Coimbra, Portugal, on 10th September 2013
6. Completion of the Final Report (the present document).

The project has drawn on the data from a series of physical tests on heat pump water heaters undertaken by the Korea Testing Laboratory (KTL). The project team is grateful to KTL for their kind assistance and cooperation for this project. The interpretation of data supplied by KTL is the responsibility of the authors.

There is considerable work to be done before internationally-comparable energy efficiency test methods, metrics and efficiency levels are at a stage where they can be used in future efficiency policy measures. A harmonisation framework is proposed for this purpose, including standardised physical tests and a staged development of simulation methods.

The impending development of an ISO test method for heat pump water heaters offers a timely opportunity to make a start on a harmonisation framework (provided the ISO consider this a priority). However, if the ISO is not considered the most suitable forum, then alternatives may be:

- The IEC, which already sets some standards for electric water heaters (but not those for heat pump technology). The IEC, like the ISO, has broad membership;
- APEC/CAST - however, this is a largely a government level structure (without direct manufacturer engagement) and the EU is not a member;
- SEAD – again, this is largely a government level structure, and China is not a member; or
- A completely new project framework, which would take some time to set up and would divert resources from other work.

It is up to the stakeholders – manufacturers, energy policy and program agencies, standards bodies and technical experts – to decide how to proceed.

We suggest the following stages:

1. This report should be sent to all the relevant standards committees and government agencies responsible for HPWH test standards, to seek their indication of:
   - whether they support the development of a Harmonisation Framework, along the lines proposed in this report, and if so:
   - where the work should be located (e.g. ISO or some other forum);
   - whether and how they wish to participate; and
   - whether they are willing to contribute resources (e.g. to support the funding of experts or product testing) to expedite the standard development process.

2. If there are sufficient favourable responses, seek an indication from ISO (or IEC, APEC/CAST or SEAD) that they are willing to host or otherwise support the harmonisation project.

3. Once a project is established, the work program could be structured as follows:
   - reach an outline agreement on a Harmonisation Protocol;
   - develop the Basic Test conditions (along the lines proposed in this report);
   - undertake round-robin testing (in at least three laboratories) of a number of HPWH units (say 6 to 10) of different configurations, testing the units to the Basic Test conditions (i.e. expanding on the KTL work for this project);
   - analyse the test results and develop a simulation model, based on parameters that can be established in laboratory testing (i.e. without relying in proprietary data);
   - validate the simulation model with the original tested units;
   - undertake a wider validation program with other willing participants (manufacturers, standards bodies and other agencies); and
   - incorporate the final method of test and simulation method in one or more standards or other published documents.

In the meantime, economies that wish to formally adopt a method of test for HPWHs, but have not already done so, should consider selecting one of the existing test methods, rather than developing a new one.

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Selected terminology, definitions and abbreviations

Add-on HPWH	See *stand-alone*
AHRI	Air-conditioning, Heating and Refrigeration Institute (USA)
All-in-one HPWH	See *unitary*
APEC	Asia-Pacific Economic Cooperation
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
AS/NZS	Australian/New Zealand joint Standard
Auxiliary heating	A secondary source of water heating in a heat pump water heater (e.g. a resistance element)
CFR 430	US Code of Federal Regulations Title 10, Part 430, Appendix E to Subpart B (which contains the method of test for water heaters specified by the US Department of Energy)
CLASP	Collaborative Labeling and Appliance Standards Program
COP	Coefficient of performance: thermal energy imparted to hot water (or delivered by the water heater) divided by electricity supplied to the heat pump water heater, under specified conditions. COP is calculated in different ways in different test standards.
DB	Dry bulb (temperature)
Domestic hot water	Water heated for the purpose of household washing, bathing and cooking
Draw-off	A withdrawal of hot water from the tank during testing or actual use (may be specified in either volumetric or energy units)
EF	Energy Factor (in USA and Canada tests) – equivalent to *COP*
Europe	The countries which are members of the European Union *or* the countries whose standards bodies are members of the European Committee for Standardization (CEN)[1]
HPWH	Heat pump water heater
Hybrid HPWH	A HPWH with auxiliary heating
Integral HPWH	A model where the heat pump, in-tank heat exchanger and storage tank are designed to work together and to be sold together, even if the parts can be separated.
KTL	Korean Testing Laboratory
MEPS	Minimum energy performance standard (sometimes called 'efficiency standard')
RH	Relative humidity – a measure of moisture content in the air relative to the maximum moisture carrying capacity at the specified DB temperature
Sanitary water	See *domestic hot water*
SCOP	*Seasonal COP*: A weighted average of COP values to reflect the energy efficiency of a water heater over a typical operating year. Different SCOP values can be calculated from a given set of COP data to reflect how a HPWH would operate in different climatic regions.
Split	A complete HPWH system with tank, where the components are not all housed in the same cabinet
Stand-alone HPWH	HPWH compressor and heat exchanger unit sold without a storage tank
Standby energy	Energy used by the HPWH compressor to compensate for standing heat loss when there is no draw-off
Standing heat loss	Energy lost from hot water during periods when there is no draw-off.
Static operation	Energy used by compressor during non-draw periods to compensate for standing heat loss
Tapping	See *draw-off*
TRNSYS	TRaNsient SYstem Simulation
Unit	A single specimen of a model
Unitary	A HPWH with the compressor, evaporator, condenser and water tank housed in the one cabinet or assembly
WB	Wet bulb (temperature) – in association with DB, a measure of humidity

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[1] Members of CEN are: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland*, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway*, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland*and United Kingdom. (*these countries are not members of the EU).

1. Overview of the Project

This project was commissioned by the Collaborative Labelling and Appliance Standards Program (CLASP), the Australian Department of Climate Change and Energy Efficiency (DCCEE) [2], the Korea Testing Laboratory (KTL) and the International Copper Association (ICA), on behalf of the Asia-Pacific Economic Cooperation (APEC) Collaborative Assessment of Standards and Testing Methods (CAST) initiative and the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative of the Clean Energy Ministerial.

It was undertaken by George Wilkenfeld & Associates, Energy Efficient Strategies and Thermal Design (Australia), Waide Strategic Efficiency (United Kingdom) ARMINES and MINES Paris-Tech (France).

Its objectives are to analyse current standards and test methods to evaluate the energy efficiency of heat pump water heaters and to prepare proposals for internationally harmonized energy efficiency test methods, metrics and efficiency levels, for use in future efficiency policy measures.[3]

1.1 Background

Heat pump technology is a far more energy efficient way to use electricity to heat water than traditional electric resistance technology. Heat pump water heaters collect energy from the ambient air, water, waste heat sources or the ground, and transfer it to water stored in an insulated storage vessel. The electricity is mostly used in the refrigeration compressor (although some units also have backup resistance elements for periods of high hot water demand or when the external conditions make compressor operation difficult).

In principle, the technology is the same as that used in conventional refrigeration and air conditioning equipment, although the operating conditions are somewhat different. Of the various types of HPWH, this report is concerned with those that collect energy from the ambient air, since these are the types which are most commonly traded internationally. It also focuses on HPWHs that are designed to serve residential rather than commercial hot water loads.

While heat pump water heaters have been available for several decades, they are becoming more popular as buyers increasingly factor energy efficiency into purchasing decisions, due to rising electricity prices and awareness of the need to reduce greenhouse gas emissions from energy use.

Heat pump water heaters – and their components – are manufactured in many countries and are widely traded internationally. The most important elements are the compressors and their controllers. These may be purchased by local assemblers, who add the cabinet, evaporator, condenser, expansion valve, heat transfer fluid, hot water storage tank and regulation system that make up a complete heat pump water heater.

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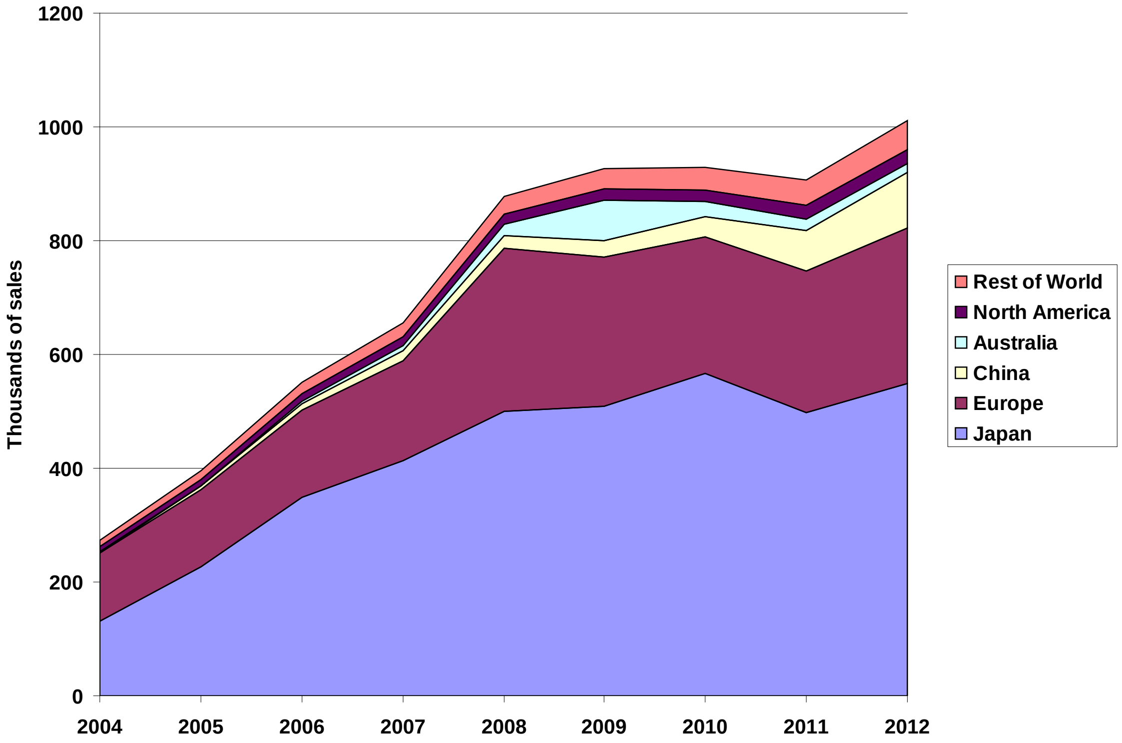
[2] Since the start of the project the relevant sections of DCCEE have been transferred to the Department of Resources, Energy and Tourism.

[3] In this report 'Test Standards' refer to the published documents which describe test methods. 'Efficiency standards' or minimum energy performance standards (MEPS) are mandatory threshold values.

Complete refrigeration units (which look like the outdoor units of split air conditioning systems) are also widely traded. Local suppliers may sell these with hot water storage tanks to make a complete water heater, or sometimes sell refrigeration units on their own for connection to existing water heaters. Complete 'unitary' or 'all-in-one' systems, where the refrigeration unit and the water heaters are housed in the one factory-built assembly, are also widely traded.

It is estimated that the global market for air to water HPWHs was about one million units in 2012. Japan accounted for about 54% of the market (almost exclusively with CO_2 refrigerant units), Europe for about 27%, China for about 10%, North America for 2.5%, Australia/New Zealand for about 1.5% and the rest of the world for 5%.[4] The market grew at about 33% per year between 2004 and 2008, and then declined due to the global financial crisis (except in Australia, where there was a brief market surge due to generous government cash incentives). Market growth resumed in 2012. .

Figure 1 Global market for air-source heat pump water heaters



The great majority of units sold globally are manufactured by large companies, most of which also make other types of water heaters. In practice there are many ways to design and assemble HPWHs, with different refrigerant fluids (e.g. R134a, R410a, R744/CO_2), operating pressures, heat exchanger characteristics, water storage volumes, heat losses and control

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[4] Author estimates, based on range of sources including E3 (2012), BSRIA (2012), Gillaux (2012) and Haier presentation to the project workshop in Beijing, April 2013.

strategies. The choice of refrigerant fluid determines the design of most of the other components, so this is a primary design decision.

The energy efficiency in operation will depend on how these complex design factors interact with:

- The usage patterns – the amount of hot water drawn off daily, and the interval between draw-offs, which is important because heat pumps can have a lower reheating rate than electric resistance elements under certain conditions;
- The climatic conditions – some designs and some refrigerants operate better at different ambient temperatures and at different humidity conditions. HPWHs are likely to be at their lowest efficiency in the coldest season, when the total hot water demand may be at its peak;
- The presence of frost and the means for dealing with it – frost build-up on the evaporator surfaces (which collect energy from the ambient air) inhibits air flow and heat transfer, so units designed to operate under conditions of low temperature must employ defrosting strategies such as the use of resistance elements, reversal of the refrigerant flow or the hot water flow, all of which carry an energy penalty; and
- The energisation profile – some designs can operate satisfactorily under tariffs where the hours of supply are restricted, while others require continuous supply.

Many design factors are pre-determined by hardware, but others are affected by the manufacturer’s or user’s control settings. As electronic controls are almost universal in HPWHs, software plays an increasing role in determining system performance in particular situations.

For globally traded products, the same physical model may be exported to different markets with different software control settings (accessible only to the manufacturer) so that the performance in each market and climate is optimised.[5] This provides a further complication for international testing harmonisation. A testing agency purchasing a unit for testing in one country may find that hidden software settings provide additional reasons for differences in results when the same model is purchased and tested in another country.

Energy-efficiency is not the only requirement of HPWHs. They must also give a satisfactory supply of hot water without the user having to wait an unacceptable time for reheats between draw-offs, and they need to be safe, durable and quiet. Some designs trade off energy efficiency for functionality, e.g. by making more use of electric resistance boosting in colder operating conditions or when hot water loads are high.

The energy-efficiency advantage of HPWHs over other forms of water heating is their main selling point, so manufacturers have an incentive to claim the highest possible level of efficiency (usually expressed in terms of COP). Several economies have developed methods to measure COP, so that manufacturers can report values on a consistent basis and their claims can be independently verified. Some of the standards which contain these energy

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[5] It is not unknown for appliance software to be designed to recognise that a unit is undergoing the energy efficiency test used in the country of destination, and to temporarily change settings to perform well under those specific test conditions. If the unit then reverts to a different – and less efficient – mode of operation in normal usage, then its is in effect circumventing the energy test. Some countries with mandatory energy labelling and MEPS programs have ‘anti-circumvention’ provisions which may disqualify or penalise products in which such behaviour is detected.

efficiency test methods also incorporate tests for noise and the ability to deliver specified volumes of hot water over specified periods.

The present study has identified six relevant national standards as well as the European standard. Two of these (Canada and the USA) are virtually identical, but the rest – Australia/New Zealand, China, Japan and Korea (draft) – differ so much that the results reported under one standard give little indication of the efficiency of the same water heater tested under a different standard.

This makes it very difficult for regulators in different economies, and almost impossible for buyers, to compare performance claims made for products tested to different standards. Without internationally harmonized (or at least comparable) test methods, the consequences are that:

- HPWHs will have to be tested under the methods of test in use in every economy to which they are exported; or
- Potential buyers will be confused by different efficiency and performance claims made under different test methods and at different operating conditions.

Either outcome would inhibit trade, add to product cost and act as a constraint on the development of the global heat pump water heater market. It will also inhibit the development and marketing of highly efficient products.

The ideal way to avoid this would be to adopt a single common method of test. In June 2013, TC86/SC6 of the International Standards Organisation (ISO) agreed in principle to develop a new test standard for heat pump water heaters.[6] However, this will take some time to develop, given the need to address different climate zones, levels of hot water use and draw-off patterns. Furthermore there is no guarantee that an ISO test, whenever finalised, would be adopted in all the countries which have pre-existing test standards, so the problem of multiple test standards may persist for some time.

Based on previous experience, the most promising and achievable objective in the medium term would be to work towards an internationally *consistent* approach to HPWH testing. The foundation of this would be a common method of testing for basic performance, e.g. the COP to heat up water from cold, under one or more standard ambient conditions in the laboratory.

The data from physical tests could possibly be used on their own to indicate product COP under a limited range of conditions. Alternatively, a specified subset of physical parameters could be accepted as the basis for performance modelling and simulation under conditions not actually tested in the laboratory.

This would enable economies to use the common physical test results to determine (or at least approximate) a model’s performance under local conditions anywhere in the world. At the least, this would enable COP values to be reported to a common metric in each market, for energy labelling purposes. Ideally the method would also be sufficiently reliable so regulators could use it to assess whether a model meets MEPS, in economies where MEPS are in force.

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[6] The IEC has also published test standards related to electric resistance water heaters (see References), but not for heat pump water heaters. Historically, the ISO has published standards for air conditioners and other products incorporating heat pump technology.

Intending exporters and local regulators could determine the energy rating of products in each market using a simulation model accepted in that market, without conducting additional physical tests.

It is unlikely that physical tests alone will deliver sufficient information to allow comparison of products under normal conditions of use in different regions (without being overly burdensome), so some modelling or computer simulation will also be necessary. While modelling involves some complexities, the principles of HPWHs operation are well understood (with the exception of the control strategies, which appear to vary substantially amongst manufacturers).

A number of proven computer simulation models exist that could be used to form the basis of an accurate and internationally agreed approach to performance simulation. However, some of the models require data that can only be obtained from the manufacturer. This makes them less useful for monitoring and compliance than models which use only those parameters that can be measured or determined by any test laboratory.

Additional levels of convergence would be achieved if:

- a single simulation model or approach were accepted in all economies; and
- there were agreed thresholds and classifications for levels of energy–efficiency (eg COPs under defined conditions that might be accepted for MEPS, and the increases in COP that define ‘higher-efficiency’ products).

For example, if the MEPS levels adopted by different economies could be compared, the least stringent of these may be designated as ‘Level 1’ efficiency. Increasing levels could then be defined by an algorithm, e.g. if 10 percentage point increase in efficiency represents an additional level. In this arrangement, if the Level 1 COP is 2.0, say, then a HPWHs which achieves a COP of 2.2 would be graded Efficiency level 2, one which achieves a COP of 2.4 would be graded Level 3 and so on.[7] Ultimately, different economies might adopt different MEPS levels according to their requirements (and energy prices), and signal their intention to move to higher levels at target dates in the future.

The development of a roadmap to meet these objectives relies on a detailed understanding of the current methods of physical HPWH testing and simulation currently in use, planned or advocated, of the differences between them and of their potential points of convergence. This is the objective of the present study.

1.2 Project Stages

This project has been undertaken in the following stages:

1. A study and systematic analysis of existing test standards for heat pump water heaters;
2. Preparation of a draft Interim Report on the above;

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[7] The algorithms may be geometric rather than arithmetical, since it becomes technically more difficult to achieve higher and higher COPs.

3. Presentation of the draft Interim Report to a Workshop of invited experts and stakeholders in Beijing, China on 12th April 2013 in association with the 41st meeting of the APEC Expert Group on Energy Efficiency and Conservation;
4. Completion of the Interim Report in June 2013, after a period for comment on the Draft. . The Interim Report is available at http://clasponline.org/apec-hpwh along with the presentations from the above workshop;
5. Preparation of a Draft Final Report.;
6. Presentation of the draft Final Report to a Workshop of invited experts and stakeholders in Coimbra, Portugal on 10th September 2013;
7. Completion of the Final Report after a period of comment on the Draft.

This project has drawn on the data from a series of physical tests on heat pump water heaters undertaken by the Korea Testing Laboratory (KTL). The project implementers are grateful to KTL for their kind assistance and cooperation for this project. The interpretation of data supplied by KTL is the responsibility of the authors.[8]

1.3 Final Report Outline

The present document is the Final Report under Task 7 above. Section 2 describes the general approaches for testing HPWHs and the many variables which need to be taken into account. It also covers the energy efficiency policies and programs which make use of the test results in each economy.

Section 3 analyses the results from the KTL test program, and summarises the outcomes of the simulation modelling undertaken for the present study.

Section 4 presents the conclusions on the scope for convergence of HPWH tests methods.

Appendix A summarises the main aspects of each existing test standard, the details of which were set out in the Interim Report.

Appendix B illustrates the physical performance of the key HPWHs tested by KTL.

Appendix C describes an approach to the energy performance modelling of HPWHs using the data from the KTL test results.

Appendix D contains the agendas and participants of the two project workshops. There were 39 participants in the Beijing workshop, from 10 APEC economies, and 27 participants in the Coimbra workshop, from 2 APEC economies and 6 other countries, mainly in Europe.

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[8] The consulant team is also grateful to the organisers of the workshops, especially Mr Pierre Cazelles (ICA, China), Mr Wei Bo (China National Institute of Standards) and Ms Paula Fonseca (University of Coimbra).

2. Existing Test Standards and Efficiency Programs

2.1 General Testing Approaches

The key energy efficiency advantage of heat pump water heaters over conventional electric water heaters is their ability to transfer more energy to the hot water than the amount of electricity they consume, because most of the energy used to heat the water is extracted from the ambient heat source (usually air, water or the ground).

The energy supplied to the water divided by the electrical energy consumed is generally called the Coefficient of Performance (COP) or the Energy Factor (EF).[9] Conventional electric resistance water heaters cannot by definition have a COP over 1.0, because all of the heat supplied to the hot water comes from an electric resistance element. A well-designed HPWH should have a COP significantly higher than 1.0. However, HPWHs are relatively complex systems, so testing and predicting their performance is not straightforward. The overall energy efficiency can vary with the following:

- the climatic conditions where it is installed;
- the temperature of the cold water supplied to the HPWH and the temperature at which it is heated;
- the performance of the heat pump/heat transfer system (compressor, evaporator, condenser and other components);
- the insulation and heat loss of the storage tank;
- the quantity of hot water drawn off each day;
- the quantity and duration of each draw and the time intervals between draws;
- the thermostat settings and the control strategy; and
- the energisation profile, e.g. whether the heat pump can run at any time[10] or whether it cannot run at certain times due to a restricted hours (off-peak) tariff.

The same HPWH can give very different COP values according to the method of test and how the results are calculated from the measurements (apart from variations in results between different laboratories). Some test standards only measure the COP during the period when the unit first heats the water from cold, some take into account the COP during a series of physical draw-off and reheating cycles, and some take into account the energy used to maintain the hot water at storage temperature during periods when no hot water is being drawn off.

As this report demonstrates, the COP values reported under one test procedure cannot be directly compared with those reported under another. A further complication is that some methods report COPs under the tested physical conditions only, while others report a ‘seasonal’ value that is weighted according to how performance is expected to change over the year, as ambient conditions, hot water loads and inlet cold water temperatures vary. This weighted value is often called the ‘Seasonal COP’ (SCOP) value.

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[9] COP can be measured over different time scales – instantaneously during the heating process, during the entire cycle of heating water from cold to hot, or over a longer period during which hot water is drawn off and more cold water is heated. The term EF usually means the last of these cases.

[10] While power may always be available, some tariffs vary by time of day, so the user control and operation strategy may be to avoid operation during very high tariff periods wherever possible.

2.2 Test Standard Parameters

2.2.1 Product Classification and Configuration

The HPWHs within the scope of this project are air to water models suitable for domestic hot water service, where the vapour compression cycle is driven by an electric motor-powered compressor. In principle, any refrigerant fluid may be used, although many refrigerants may be restricted in domestic situations due to safety and other requirements (e.g. China Standard GB/T 23137–2008 has special construction requirements for CO_2 units due to their high operating pressures). While all the standards under consideration agree on this point, they define and classify products according to the criteria below (summarised in Table 7).

Configuration

- Unitary (refrigeration unit and water storage tank in the one cabinet);
- Split – heat pump connected to tank by refrigerant lines, condenser inside water tank;
- Split – heat pump connected to tank by water lines, condenser housed in same cabinet as evaporator. This configuration may be designed as
    - single pass (‘one time’) – water heated to desired temperature in one pass; and
    - multi-pass (‘circulated’) – water heated to desired temperature in stages.

Duty and Capacity

The aspect of HPWHs that is the subject of this project is the capacity to provide hot water, i.e. water at the temperatures and in the quantities needed for the typical washing, bathing and cooking needs of a single household.

Some HPWHs may be defined as ‘commercial’ in that they can provide larger quantities of hot water or at a higher temperature. However, the criteria are not always clear. The US AHRI standard 1301 defines a commercial heat pump as one where the input capacity does not exceed 50 kW, and which is not covered by US Regulations 10 CFR Part 430. China Standard GB/T 21362–2008 defines a ‘Commercial & Industrial’ HPWH as one with ‘nominal heating capacity of 3000W and above’. Many HPWHs sold to the residential market have a far greater heating capacity than this limit. Furthermore, some domestic HPWHs can be easily adapted for commercial use by adding multiple storage tanks.

Some HPWHs are also designed to provide hot water for space heating purposes (under-floor coils or radiators) as well as sanitary hot water. Some standards allow HPWHs to be tested while in one or other of these operating modes, but to date there is no standard for testing a HPWH that is simultaneously serving a domestic water heating load and a space heating load.

Auxiliary Heat Source

Some HPWHs have an auxiliary heat source, usually an electric resistance element, which can supplement the vapour compression cycle during the initial heating of water from cold, during periods of high hot water demand or when the vapour compression cycle is unable to operate effectively (e.g. under frost or very low external temperature conditions). Such HPWHs are sometime called ‘hybrid’ models.

The operation of the auxiliary heater may be automatic or manually controlled. For user-selectable heat sources, the setting for the tests is not always clear. For example, it may be possible to switch the element on for the tests of hot water delivery capacity and reheat times, but switch it off for the tests of energy-efficiency. While this would be misleading, not all test standards explicitly prevent this anomaly.

‘Smart’ Controls

Water heaters are now being designed with control logic that can adapt to the pattern of household hot water use. For example, if the controller observes that hot water demand is concentrated at a certain time of day it can adapt reheat times to minimise heat loss or to make use of cheaper electricity rates (assuming that there is a capability for the water heater to have tariff times programmed into it, or to monitor them in real time).

The proposed European regulations for the energy labelling of water heaters (including HPWHs) allows models with ‘smart controls’ to obtain a rating one grade higher than would be indicated by energy efficiency alone (EC 2013). It defines ‘smart control’ as ‘a device that automatically adapts the water heating process to individual usage conditions with the aim of reducing energy consumption’.[11]

While ‘smart’ controls may enable a water heater to reheat at times when electricity tariffs are lower use, and so reduce running costs, they complicate energy efficiency testing because the water heater may behave differently after ‘learning’ the draw-off patterns used in the first stages of a test.

Impact of Configurations

The way in which HPWHs are defined varies significantly between standards (see Appendix A) This means that products which are grouped together for testing under one standard may need to be separately tested under a second standard, because of some design difference that may not even be defined under the first standard. Furthermore, a product type defined in one standard may not even be testable under other standards, because there is no provision for them. For example, the European Standard EN16147 does not appear to provide for the testing of a unitary HPWH designed to be installed outside, whereas this product type is common in Australia.[12]

2.2.2 Physical Energy Performance Testing

In general, physical test standards fall into two groups: those where the HPWH only heats up the water from cold, and those which involve actual draw-offs of hot water and subsequent reheating.

Of the tests currently in use, the Australian and New Zealand standard AS/NZS 5125 and the Chinese standard GB/T 23137 involve a heat-up test only. The Canadian, European, Japanese

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[11] Some new water heaters have the capability to change their mode of operation (i.e. to turn off, reduce load or turn on) in response to signals sent from the utility or other ‘remote agent’. This is a separate capability that does not impact on energy consumption or energy-efficiency.

[12] The test conditions in Table 5 of EN16147 specify 20ºC ambient temperature for the storage tank but 7ºC ‘outside air’. These conditions can only be maintained if the tank and the evaporator are physically separated.

and USA test standards all involve hot water draw-offs. The final version of the Korean (KS) test being developed may include drawoffs, although the early version did not.

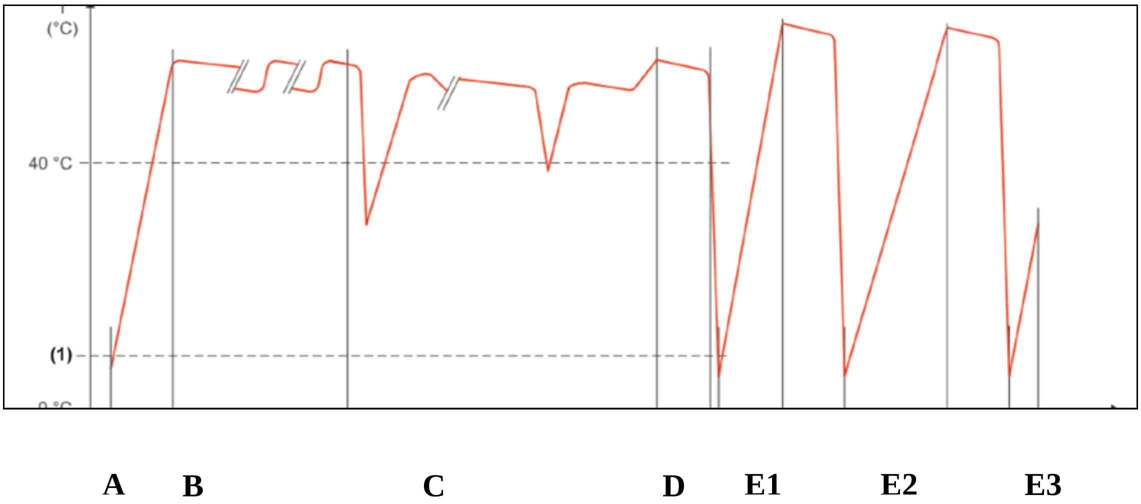
The interim report for the present project (CLASP 2013) gives a detailed account of the test procedure in each of the above standards. Appendix A in the present report summarises each test procedure.

The most detailed physical energy tests involve all of the following stages (illustrated as a sequence in Figure 2, adapted from EN16147):

A. the heating up period;
B. the determination of 'standby' (or 'static operation') energy to compensate for heat loss while the hot water is untapped;
C. the hot water 'tapping' or draw-off sequence;
D. maximum quantity of water that can be drawn off before the temperature of the flow falls below a specified threshold;
E. tests to determine the rate of reheat.

Not all test standards include all of these stages, or perform them in the same order. Some standards include multiple sequences of energy tests under different operating conditions, including conditions which induce frosting on the evaporator.

Figure 2 Typical stages in HPWH testing



Ambient temperature and humidity

The temperature and humidity at the evaporator is one of the main determinants of the performance of an air-source HPWH, because the evaporator collects the heat from the ambient air and transfers it into water. The less heat in the ambient air, the harder it is to collect and concentrate. Some HPWH designs and some refrigerant fluids will operate well at low ambient temperatures, while others operate better at higher temperatures.

Humidity is also a major factor. At higher temperatures, humidity assists the performance of a heat pump by increasing the thermal mass passing the evaporator and by transferring some latent heat to the evaporator through condensation. On the other hand, high humidity is not helpful at low temperatures (1ºC to 2ºC) as frost will form on the evaporator. Below 0ºC, humidity condenses out and air is relatively dry, so defrosting can be less frequent – although the operating COP will usually deteriorate.

'Frosting' is the formation of a thin layer of ice which becomes a physical barrier to air flow over the evaporator as well as an insulating barrier that inhibits heat transfer. Simulating performance beyond the point where frosting commences is not usually possible, as a number of non-linear effects come into play, so physical tests under frosting conditions are usually necessary if the product is intended for use in these conditions.

Every test standard specifies the ambient temperature and humidity for at least one test condition. Of the existing HPWH test methods analysed, the Australian/New Zealand standard has the greatest number of test conditions: four mandatory test conditions and one additional 'low temperature' test for products that the manufacturer claims are 'suitable for low ambient temperature operation without auxiliary boosting'. The Chinese standard specifies *up to* four conditions, and the Japanese standard three conditions. The Canadian, USA and European standards each use a single test condition.

A single test condition may not be sufficient to indicate the performance of heat pumps which may be sold across a wide geographical area and therefore operate in very different conditions. The Northwest Energy Efficiency Alliance (NEEA) in the USA has published a supplementary test (at an ambient of 50°F or 10°C) for HPWHs intended for sale in that region (NEEA 2011). For the purposes of its proposed energy labelling program, the European Commission has added two extra test conditions to the single test in EN16147 (EC 20913).[13]

Instrumentation and Heat-up

It is relatively easy to measure the amount of electricity supplied to a HPWH over a given time period, but more difficult to measure the amount of energy effectively transferred to the water, how much is available for drawing off as hot water and how much is lost If more measuring instruments are used, they are of higher accuracy and/or the frequency of readings is increased, then it is possible to gain a better understanding of how energy flows through the water heater, and it becomes easier to replicate the test results and estimate the performance under different conditions.

Table 8 shows that the Australian and New Zealand, Canadian and USA test standards require 6 sensors to be inserted into the tank at precise locations, while the Chinese and European test standards do not specify a number or a location for sensors, making repeatability more difficult. The Japanese standard and the draft Korean test standards focus on measurement of the water temperatures at the inlet and outlet of the water heater during draw-offs The Japanese standard encourages, but does not mandate, the measurement of water temperatures at multiple positions in the tank, to quantify the heat stored.

Most HPWHs have a user-adjustable temperature control (usually a thermostat) that determines the temperature at which heating stops. The Australian and New Zealand standard specifies that HPWHs be tested at the maximum setting, whereas the other standards specify a fixed temperature – as low as 50°C in the Korean test (unless the manufacturer states

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[13] It is understood that EN16147 will be revised to match the EC 2013 Ecodesign Regulation.

otherwise) to 65°C for CO_2 refrigerant units in the Chinese test, and more than 65°C in the Japanese test. In the European standard, temperature is set according to the manufacturer's instructions.

Tapping or draw-off

The tapping or draw-off schedules represent a major difference between tests (see Table 9). The range is from no tapping at all (China and Korea), one draw repeated 6 times (Canada and USA), and multiple combinations of tapping schedules and ambient conditions (Japan and Europe). The present versions of Australian and New Zealand standards do not include a physical draw-off test, but account for tapping in seasonal modelling.

Some standards specify a single flow rate for all tappings, while others specify lower flow rates for smaller-volume draws and higher flow rates for higher-volume draws. The flow rate can have a significant impact on performance, because higher flow rates will cause more mixing, or 'de-stratification' of the water in the tank, so the temperature of water drawn off may be affected.

The inclusion of a tapping load in a standard can have several objectives:

- to collect data on how the water heater responds to a typical draw, so that this can be used in further calculations or modelling;
- to test the extremes of performance (e.g. how much 'hot' water above a specified temperature it can deliver in each draw, and how quickly it can recover to the point where hot water can be draw off again); and
- to simulate performance in actual use.

As hot water use is highly variable (both within a household and across households), there is no guarantee that any given tapping pattern (or patterns) will be statistically representative of actual use in a given population of households even in the one country, let alone between countries.

Heat loss and Standby

The in-use energy efficiency of a HPWH depends on its ability to retain stored heat as well the incremental energy to heat water from cold. Some test procedures measure the energy required to maintain the stored hot water at the maximum setting of the thermostat or temperature controller when no water is drawn off. This is influenced by both the heat loss of the tank and the energy-efficiency of the heat pump at what is usually its least efficient operating point.[14] The Australian and New Zealand test does not determine heat loss in this way, but cross-refers to a separate standing heat loss test (AS/NZS 4692.1).

Other Requirements

A HPWH may be energy-efficient but may reheat very slowly, so determining its capability for reheating is important. The quantity of hot water which a HPWH can supply over a given

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[14] The terms 'standby', 'static operation' and 'standing heat loss' are used to mean different things in different standards, and these terms are not always clearly defined.

time period depends on both its storage volume and the rate at which it reheats from a specified cold water inlet temperature.

Draw-off tests can measure reheating capability directly, and can also account for temperature drop by discarding hot water when it falls below a specified temperature (which differs between tests). The Australian and New Zealand standard does not directly test delivery capacity, but the simulation based on the test results does model when the flow would drop below specified limits.

The Chinese, European and Japanese standards include additional requirements, beyond those strictly related to performance and energy efficiency. These include:

- Testing the air-tightness of the refrigeration system using a leak detector;
- Pressure-testing the water tank (both static and pulse pressure tests);
- Noise testing in an anechoic chamber;
- Testing the durability of the packaging;
- Risk of water contamination;
- Corrosion resistance to salt spray when the HPWH is installed in a coastal environment;
- Durability of the external finish;
- Mechanical safety and stability;
- Electrical safety; and
- Flammability.

Finally, a number of standards include requirements for permanently marking products with key design and performance characteristics. While these additional specifications are important in terms of general performance, usability and safety, they may not relate directly to energy efficiency.

2.3 Energy Efficiency Programs based on Standards

Table 1 gives an overview of the HPWH test standards in use by various economies and under development and the programs and purposes for which they are currently used.

The energy efficiency metrics (COP, SCOP and EF) derived from the test standards are used in a number of ways to promote greater energy efficiency in heat pump water heating in different countries:

- Minimum energy performance standards (MEPS) included in the test standard itself. This means that a product cannot comply with the standard unless it meets those MEPS levels. The Chinese test standard is an example of this.

- Legally binding MEPS levels imposed by legislation that refers to a specific test standard. The proposed European Directive on *ecodesign requirements for water heaters and hot water storage tanks* (EC 2012) is an example of this.

- Mandatory energy labelling that refers to a specific test standard (e.g. the European *ecodesign requirements* and the US EnergyGuide label).

- Voluntary endorsement and/or labelling regimes, where participation is not legally required but has a high commercial value to product suppliers. Examples include the Energy Star labelling program in the USA, European TopTen and Japanese TopRunner programs and the Australian Renewable Energy Target.

As these programs are likely to drive the use of HPWH standards in future (see Table 1), they are described in the following sections. Apart from these national and international programs, many other schemes, such as energy utility rebates for the purchase of higher-efficiency heat pumps or building code requirements, also refer to the standards and performance criteria, either directly or indirectly (e.g. by limiting eligibility to products that meet voluntary endorsement criteria).

2.3.1 Australia and New Zealand

The Australian and New Zealand Standard AS/NZS 5125 determines COPs for HPWHs as they heat up under 5 separate test conditions. The COPs are not published on their own, but the test results are used as inputs for the modelling procedure described in AS/NZS 4234. This determines the annual electricity use of the HPWH under a range of usage and climate conditions and compares it with the notional electricity use of a reference electric resistance water heater performing the same water heating task.

The output value is expressed in terms of ‘% electricity saved’ compared with the reference electric water heater, even though it could just as easily be expressed as a SCOP value. The standards have evolved to support the Federal Government’s Mandatory Renewable Energy Target, which requires a certain percentage of electricity supplied to be generated from eligible renewable energy sources. HPWHs and solar-electric water heaters are declared eligible to contribute to this requirement, and the ‘% of electricity saved’ is treated as if it were generated from a zero-emissions source. (The majority of Australia’s electricity is generated from coal, so the electricity supply has a high emissions-intensity).

Table 1 Overview of standards, MEPS and labelling for heat pump water heaters

Country/Economy Test Standard (a)	Physical testing	Derivation of COP/SCOP	Requirements in standard itself (g)	Requirements outside standard (h)	Economies where these standards used
Australia & New Zealand (b)	No draw-off (e)	Seasonal Performance modelled (but not reported as SCOP)	Proposed - labelling standard under development	Voluntary – eligibility under Renewable Electricity Act	Australia, New Zealand
	Draw-off test under development	COP calculated	Proposed - MEPS under development		
Canada (c)	Draw-off	EF calculated	Proposed – will impact HPWHs from April 2015	Voluntary – Energy Star endorsement energy label	Canada
China	No draw-off	COP calculated	Yes	No known program for HPWHs	China, Chinese Hong Kong
Europe (b)	Draw-off	COP calculated	No	Voluntary – Top Ten endorsement Proposed – mandatory energy labelling and MEPS	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.
Japan	Draw-off	SCOP calculated	No	TopRunner standards	Japan
Korea (d)	Under development	COP calculated	No	No known program for HPWHs	Republic of Korea
USA (c)	Draw-off	EF calculated	Proposed – will impact HPWHs from April 2015	Mandatory – EnergyGuide label Voluntary – Energy Star endorsement energy label	USA
ISO	Under development	To be determined	To be determined	To be determined	Standards not yet developed

(a) See detailed descriptions in Appendix A. (b) Standard officially applies to two or more economies. (c) Separate standards but essentially the same test (d) In draft – not yet published. (e) No draw-off during testing. Load patterns are simulated in seasonal performance modelling. A revision of the test standard is under way. It is planned to include draw-off tests for the purpose of determining minimum energy performance (MEPS) levels. (g) Where energy labelling and/or MEPS are included in the standard itself, so that products failing to meet those requirements are considered non-compliant with the standard. (h) Where laws or regulations state that a product must be tested using a given standard, but any MEPS and/or labelling requirements are in the regulations, and so can be altered without changing the test standard.

Only models which achieve a threshold level of 60 % ‘electricity saved’ are eligible to benefit from the scheme. The value of the benefit is around $1,000 AUD per unit sold, so although participation is voluntary nearly all suppliers have registered their models because of the commercial advantage of doing so.

Australia and New Zealand are currently considering introducing mandatory energy labelling and MEPS for HPWHs, and a cost-benefit analysis has recently been published.[15] As part of this process, AS/NZS 5125 is being revised so that it will include draw-off tests (the likely conditions are given in Table 8). The COP values established under this revised test method will determine whether a model complies with the mandatory MEPS levels, which are still to be set.

The Australian and New Zealand governments are also considering a system of mandatory energy labelling for HPWHs. Although this is yet to be finalised, the calculation of the energy efficiency level may rely on a combination of physical data measured in accordance with AS/NZS 5125, and simulation modelling. This would allow the method of rating HPWHs to be compatible with other types of water heater, which is a policy objective in other economies as well.

2.3.2 Canada and United States

The Canadian standard and the near-identical US test (which is published as a Federal Regulation rather than a standard) determine Energy Factors for HPWHs. At present these standards specify a minimum EF of:

$$0.97 - (0.00132 \text{ x Rated Storage Volume in gallons})$$

A 55 US gallon (208.2 litre) water heater, for example, would have to meet an EF of 0.897, which would be within the reach of a well-insulated electricity resistance storage water heater. From 16 April 2015 electric water heaters with a Rated Storage Volume of 55 gallons or more will have to meet a minimum EF of:

$$2.057 – (0.00113 \text{ x Rated Storage Volume in gallons})$$

A 55 US gallon water heater would have to meet an EF of 1.995, which is only achievable by a heat pump or possibly a solar water heater. Therefore this will become the effective MEPS level for larger HPWHs, although HPWHs smaller than this will only have to meet an EF of:

$$0.96 - (0.0003 \text{ x Rated Storage Volume in gallons})$$

This means a 50 gallon HPWH would have to meet an EF of 0.945, which is not particularly challenging for a heat pump, and may in fact be achievable by a highly insulated electric storage water heater.

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[15] http://www.energyrating.gov.au/blog/2013/07/19/heat-pump-water-heaters-consultation-ris-submissions-by-2-sept-2013/

Table 2 Current and proposed MEPS levels, residential water heaters, USA

Product Class	Rated storage volume (US gal)	Energy Factor	Rated storage volume (US gal)	Energy Factor
Gas-fired	20 to 100	0.67-(0.0019*V_S)	20 to 55	0.675-(0.0015*V_S)
			>55 to 100	0.8012-(0.00078*Vs)
Oil-fired	Up to 50	0.59-(0.0019*V_S)	Up to 50	0.68-(0.0019*V_S)
Electric	20 to 120	0.97-(0.00132*V_S)	20 to 55	0.96-(0.0003*V_S)
			>55 to 120	2.057-(0.00113*V_S)
Table-top	20 to 100	0.93-(0.00132*V_S)	20 to 100	0.93-(0.00132*V_S)
Instant Gas	<2	0.62-(0.0019*V_S)	<2	0.82-(0.0019*V_S)
Instant Elec	<2	0.93-(0.00132*V_S)	<2	0.93-(0.00132*V_S)

These are minimum efficiency levels only. The Energy Star criterion for heat pump water heaters is an EF of 2.0 or higher (EPA 2009). It is not known whether this will be revised once the MEPS levels in the US standards are raised. At the time of writing there were 10 HPWH models listed as Energy Star compliant, with EFs ranging from 2.5 to 2.2.[16]

In early 2013 the US Department of Energy sought information on the test procedures for residential and commercial water heaters.[17] Among the responses was a proposal from the Air-conditioning, Heating and Refrigeration Institute (AHRI) to replace the current 6-draw schedule in CFR 430 with 12 irregularly spaced and draws of different volumes, to simulate actual (or at least more typical) use.

In 2103 the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) published a new Standard 206 *Method of test for rating of multi-purpose residential heat pumps for space conditioning, water heating and dehumidification* (ASHRAE 2013). This standard applies to electrically powered unitary heat pump equipment that is capable of providing space conditioning, water heating and dehumidification functions, but can heat water without requiring the simultaneous performance of other functions. It addresses air-source, watersource, ground water-source, ground-source closed loop, and direct geoexchange equipment rated below 65,000 Btu/h (19 kW).

The standard provides a uniform method of testing for rating seasonal efficiency of multipurpose heat pumps. It is understood that the ASHRAE, together wth the AHRI and the US Department of Energy, is reviewing the test procedures on which future water heater and heat pump water heater performance will be evaluated.

2.3.3 China

The Chinese test standard GB/T 23137-2008 specifies that the measured COP of air source heat pump water heaters under nominal operating conditions should be not less than 3.70 for products using ‘one time heating’ and ‘circulated heating,’ and not less than 3.40 for products using ‘static heating’ (see definitions, Appendix A).

Heat pump water heaters are not currently required to be energy labelled under the China Energy Label (http://www.energylabel.gov.cn/en/index.html).

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[16] https://www.energystar.gov/productfinder/product/certified-water-heaters/?scrollTo=0&search_text=&sort_by=energy_factor&fuel_filter=Electric&type_filter=&brand_name_isopen=&input_rate_thousand_btu_per_hour_isopen=&page_number=0&lastpage=0

[17] http://federal.eregulations.us/rulemaking/document/EERE-2011-BT-TP-0042-0028

2.3.4 Europe

The standard EN 16147 specifies the tests for determining COP and other aspects of performance, but does not specify minimum values for these. It does specify that if the manufacturer decides to provide information about the performance of a model it must be with reference to one of the standard draw-off schedules.

The European TopTen scheme, which is supported by agencies of the European Commission, awards 'TopTen' designation to HPWHs which achieve a COP of at least 2.3 when tested to EN16147.[18]

The Ecodesign Directive currently before the European Commission specifies a staged implementation of ecodesign requirements for MEPS and maximum sound power level for *combination* heat pumps (i.e. those capable of space heating as well as water heating), but not yet for heat pump water heaters only (EC 2012a). However, a Regulation Supplementing Directive 2010/30/EU currently before the European Commission specifies the energy labelling of water heaters, including HPWHs (EC 2013).

The water heater label includes the energy rating on a scale of A to G, or A+ to F. This indicates the 'water heating efficiency class' of the water heater on the declared load profile. The range of test conditions includes those on EN16147 (see Table 9) but does not actually refer to it, and adds additional test conditions beyond those in the standard:

- Two additional temperature test conditions in addition to the one in Table 8 (which the Directive calls 'average climate conditions'): 'colder climate conditions' (2°C DB/1°C WB) and 'warmer climate conditions' (14°C DB/13°C WB); and
- Three additional load profiles smaller than S (these are called XXXS, XXS and XS).

Table 3 Proposed European water heating efficiency classes for all water heater types

Draw-off profile	**Efficiency required to achieve this rating**									
	G	**F**	**E**	**D**	**C**	**B**	**A**	**A+**	**A++**	**A+++**
M	<27%	>=27%	>=30%	>=33%	>=36%	>=39%	>=65%	>=100%	>=130%	>=163%
L	<27%	>=27%	>=30%	>=34%	>=37%	>=50%	>=75%	>=115%	>=150%	>=188%
XL	<27%	>=27%	>=30%	>=35%	>=38%	>=55%	>=80%	>=123%	>=160%	>=200%
XXL	<28%	>=28%	>=32%	>=36%	>=40%	>=60%	>=85%	>=131%	>=170%	>=213%

Source : EC (2013) Applies to packaged water heaters under average EN 16147 climate conditions (Table 8)

The larger the load profile, the higher the energy factor that a model must achieve to attain a given rating. The A+ to A+++ classes can only be reached by water heaters using renewable energy sources (i.e. either HP or solar water heaters). The energy efficiency classes above A are defined such that the classes A+/A++/A+++ correspond to a contribution of 35 %/50 %/60 % of renewable energy sources to energy consumption, compared with energy efficiency class A.

The HPWH energy label will also have the following information:

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[18] http://www.topten.eu/english/criteria/selection_criteria_electric_water_heaters.html&fromid=

- A pictogram indicating the load profile on which the HPWH was tested (e.g. a single tap for a low load, a series of taps, showers and a bath for a large load);
- The noise levels (in dB) from both the internal and external components of the heat pump;
- The annual energy consumption (in both kWh/annum and GJ/annum) for each of the average, warmer and colder climate conditions (calculated in accordance with the Directive);
- A map of Europe indicating the colder, average and warmer climate zones; and
- An indication whether the HPWH is suited to operate with off peak tariffs.

2.3.5 Japan

The Japan TopRunner Program covers a wide range of products, including heat pump water heaters.[19] The program sets standards based on the best available models currently on the market, with the intention that all models must meet those levels of energy efficiency within 5 years. For HPWHs, the criteria are based on tests according to JIS C 9220 (see Appendix A). The efficiency levels to be reached in 2017 are indicated in Table 4.

Table 4 Japan Top Runner target HPWH COP values for 2017

	Normal size household (a)	Small size household (a)
Normal climate	3.0	2.8
Cold climate	2.6	2.4

Source: METI (2012). Values above are for models with a single storage tank of <= 240 litres and no 'heat exchange' function. Other target values apply to other configurations. (a) As classified by draw-off (Table 8).

2.3.6 Korea

Heat pump water heaters are not subject to energy labelling or MEPS in Korea at present. It is possible this may change once the current draft test standard is completed.

2.3.7 Thailand

The Thailand building regulations specify that heat pump water heaters installed in new buildings with a size greater than 2,000m^2 (including condominiums) shall have a minimum COP of either 3.5 (if the hot water delivery temperature is 50°C) or 3.0 (if the hot water delivery temperature is 60°C). The cold water supply and air temperature are both stated to be 30°C, but no other details of the test are given (Thailand 2009).

Thailand also has a tax incentive program to support the HPWH market. Buyer of registered heat pump models that have a COP of either 3.5 (if the hot water delivery temperature is 50°C) or 3.2 (if the hot water delivery temperature is 60°C) can claim the tax back. The committee administering the tax incentive has absolute discretion on the testing method that manufacturer may use to get the COP value.[20]

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[19] http://www.eccj.or.jp/top_runner/pdf/tr_heat_pump_sep2012.pdf

[20] Personal communication, Dr. Pongpan Vorasayan, Engineer Bureau of Energy Regulation and Conservation, Department of Alternative Energy Development and Efficiency (DEDE), Thailand Ministry of Energy.

2.3.8 Development of ISO test standard

ISO TC86/*SC6 Testing and Rating of Air-Conditioners and Heat Pumps* agreed at its meeting on 14 June 2013 to develop a test standard for air source heat pump water heaters. The scope of the standard is currently being determined – whether to cover the domestic water heating task only or the possibility of a space heating task as well.

It will take some time to develop the standard, given the need to address different climate zones, levels of hot water use and draw-off patterns. Furthermore there is no guarantee that an ISO test, whenever finalised, would be adopted in any of the countries which have pre-existing test standards.

3. Comparing performance across test standards

3.1 Physical tests

Korean Testing Laboratory (KTL) is currently developing a Korean Industrial Standard (KS) method of test for heat pump water heaters. As part of the project KTL applied a number of test methods to three heat pump water heaters (see Table 5) and made the results available for the present project.

Table 5 HPWH models tested by KTL

	Model A	**Model B**	**Model C**
Configuration	Unitary	Stand-alone (split)	Stand-alone (split)
Power supply	220-240V, 50 Hz	220-240V, 50 Hz	415V, 50 Hz (3-phase)
Refrigerant	R134a	R407c	R407c
Storage volume (litres)	190 (integral)	200 (external)	200 (external)
Storage volume (US gallons)	50.2 (integral)	52.8 (external)	52.8 (external)
Total rated power input	3.5 kW	9.5 kW	14.0 kW
Compressor power	0.7 kW	2.8 kW	4.5 kW
Control temperature	Max 60ºC	Max 55ºC	Max 65ºC
Electric resistance element	3.0 kW (switchable)	None	None
Economy of manufacture	China	China	Korea
Intended market areas	China, Europe, ANZ	China	Europe, Korea

KTL was asked to undertake the AS/NZS, European, Japanese and USA tests on each of the three units (in addition to the testing to the draft KIS standard). KTL used the method of test specified in each of these standards, but was requested to add instrumentation and collect additional data beyond what some of the standards required to allowable comparability of data across the test procedures.

Water temperatures inside the tanks was recorded with an array of 6 evenly spaced temperature sensors, as specified in AS/NZS 5125 and CFR 430.[21] The other test methods only use a single sensor or a pair of sensors close to the centre of the tank, which do not give sufficient information about the total heat stored in the tank (stratification) and how this changes over time. Temperature and energy data were recorded at 1 second intervals. This is more frequent than any of the standards specify. Some do not specify a measurement frequency at all.

The KTL testing program revealed a number of issues relevant to the interpretation and conduct of various HPWH standard tests, even by experienced and well-equipped laboratories, including:

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[21] CFR 430 states that: ‘A temperature sensor shall be positioned at the vertical midpoint of each of the six equal volume nodes within the tank. Nodes designate the equal volumes used to evenly partition the total volume of the tank.’

- Misinterpretation of the documented test procedures. This may be due to language issues or simply the expectations that test procedures have more in common than they do. For example, the unitary model was at first tested with an external tank.

- Ambiguity in the documented test procedures. For example, the unit with backup element was tested with the element in the 'on' position (i.e. under control of the HPWH) for the AS/NZS 5125 tests rather than disabled (or set to the 'off' position, which was one of the user-selectable settings). On checking, it was found that the authors and regular users of AS/NZS 5125 have agreed among themselves that supply to the elements will be cut off for testing, but that this is not actually stated in the text of the standard.

- Gaps in test procedures. It was confirmed that there is no explicit method of test in EN16147 for a unitary system that is designed to be installed outside (i.e. where the evaporator and the water tank are in the same ambient conditions) – only where colder outside air is ducted to an internally located unitary tank.

- Difficulty of obtaining the specified storage tanks for 'add-on' or stand-alone HPWHs. For example, Clause 4.10 of CFR 430 specifies that 'the tank to be used for testing a heat pump water heater without a tank supplied by the manufacturer…shall be an electric storage-type water heater having a measured volume of 47.0 gallons ± 1.0 gallon (178 liters ± 3.8 liters); two 4.5 kW heating elements controlled in such a manner as to prevent both elements from operating simultaneously; and an energy factor greater than or equal to the minimum energy conservation standard (as determined in accordance with Section 6.1.7) and less than or equal to the sum of the minimum energy conservation standard and 0.02.' As no such water heater was readily available, KTL tested the stand-alone units with a 200 litre tank (slightly larger than specified in CFR430), and both well-insulated and poorly insulated tank versions.

These issues should be kept in mind when interpreting the results of the tests (Table 6).

Table 6 Test results reported by KTL

Standard	Ambient conditions (f)	COP, Model A	COP, Model B	COP, Model C
AS/NZS 5125	TC 1 (<10ºC)	1.66 (a) 2.63 (b)	2.48	2.89
	TC 2 (18-20)	1.84 (a) 3.19 (b)	2.99	3.51
	TC 3 (30-35, WB 30-40)	1.94 (a) 3.48 (b)	3.34	3.89
	TC 4 (30-35, WB 65-75)	1.99 (a) 3.76 (b)	3.61	4.31
CFR430	19.7ºC ± 0.6ºC	2.17 (c)	1.63 (c)	1.58 (c)
EN16147	20ºC ± 2.0ºC	2.95	2.01	1.86
JIS 9220	16ºC ± 1.0ºC	2.68	2.24	1.81
KIS Draft	Standard 7ºC (d)	(e)	2.04	0.62
	Cold zone -15ºC (d)	(e)	0.67	1.31

TC = Test Condition. (a) Task COP over entire heat-up cycle, including effect of element operating part of the time. (b) COP at final stages of the heating cycle when only heat pump is operating. (c) EER (d) Domestic hot water supply only – draft standard also provides for testing space heating duty. (e) Does not perform as required at this condition. (f)

The results in Table 6 are illustrated in Figure 3. For Model A, two COP values are given for the AS/NZS 5125 test: the task COP (which includes the energy use of the heating element) and the COP for the period when the elements has ceased operating and all further heating is done by heat pump alone. The resistive element typically operates for the first 10% to 25% of the heat-up cycle (see Appendix B). If it were not operating at this time the COP of the heat pump would be at its maximum, because the temperature differential between the cold water and the ambient air is at its widest. Therefore, had the water heater been tested with the element off (as *intended* but not actually stated in AS/NZS 5125) the COPs for Model A would have been higher – probably similar to Model C. The AS/NZS 5125 COPs reported for Models B and C correspond to the intention of the test standard, because they do not have heating elements.

The European EN 16147 test used the L draw-off pattern (24 draws totalling 11.66 kWh per 24 hours – see Table 9). On this test, Model A showed a COP of 2.95, significantly higher than Models B or C. In fact, Model A appears to comfortably exceed the Euro TopTen criterion of 2.3 COP on the EN 16147 test, while Models B and C fall below.[22]

Model A also scores well on the USA CFR 430 test: its apparent EER of 2.17 meets the April 2015 MEPS level of 2.17 for HPWHs for a 55 gallon unit (although the capacity of Model A is only 50.2 gallons, so it would be exempt from the MEPS requirements in Table 2). In fact Model A would meet current EPA Energy Star criteria for HPWHs, which is an EER of 2.0. Currently, the highest rated HPWH on the Energy Star list has an EER of 2.4.

As tested, the stand-alone Models B and C would fail to meet the 2015 MEPS levels (although this could change if the type of tank specified in CFR 430 were used). Figure 3 indicates that using a poorly insulated tank for the CFR tests results in a significant reduction in calculated EER – in this instance, of 0.6 to 0.7.

Model A also scores higher on the JIS test than either Models B or C. In fact, Models B and C reverse their rank order on a number of the tests:

- Model C ranks higher than Model B at all four AS/NZS 5125 test conditions;
- Model B ranks higher Model C on the EN 16147 test;
- Model B and C rank very closely on the CFR 430 test (possibly due to the high influence of the storage tank on the results);
- Model B ranks higher Model C on the JIS C 9220 test;
- On the draft KS test, the ranking reverses according to whether the ‘standard’ or ‘cold’ ambient conditions are used.

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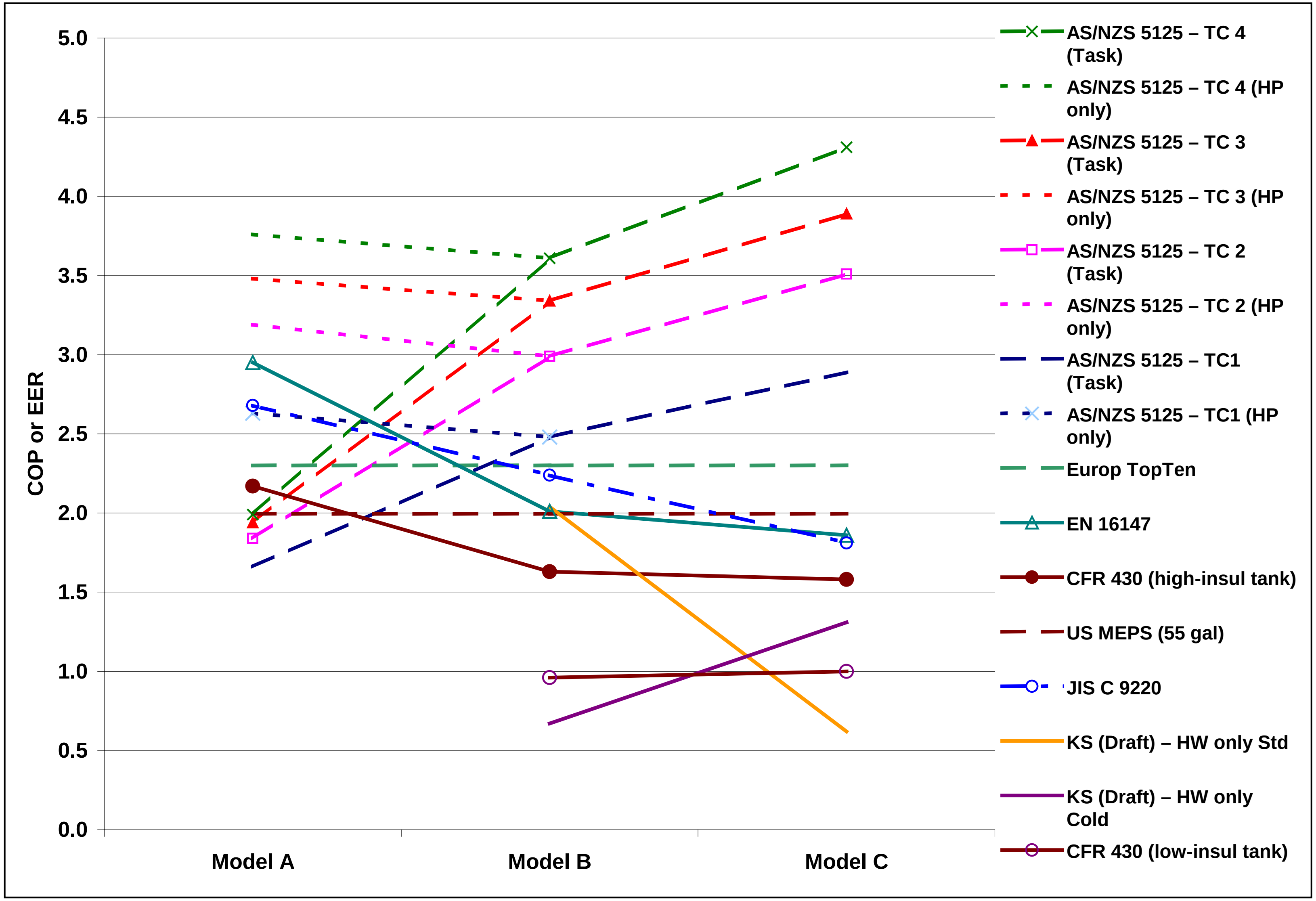
[22] As at August 2013, the highest COP claimed by a HPWH model listed on the TopTen website was 3.8. Neither Model A nor any other product from the manufacturer of Model A appears on the Euro TopTen website.

Figure 3 Summary of physical test results



3.2 Modelling

The raw data from the KTL tests was analysed in detail by the project team, and combined with other information in order to establish the scope for computer simulation to form the basis for test harmonisation. The full analysis is presented in Appendix C.

The ‘reference’ data was that collected by KTL during the testing of each of the three models in Table 5 to AS/NZS 5125. This is because this standard has the largest number of test conditions (4) and requires the highest level of instrumentation in the tank (6 sensors), so provides the most detail on product performance during the heat-up phase. However, as the present version of AS/NZS 5125 has no draw-offs, all data on performance during actual draw-offs came from tests to the European, US and Japanese test standards.

This simulation method derived from the AS/NZS standard test data for HPWH Models B and C was used to estimate the COP that would be expected when the same water heaters were tested in accordance with other test procedures. The estimates were compared to experimental data measured for the water heaters tested under the other standards; specifically the heat-up phases of the US, Japanese and European test standards and the steady-state Korean test standard. The simulation results produced were in close agreement with the measured data.

The method was also used to simulate performance over a full test cycle including a draw off pattern. This required the modelling of electric power model and tank heat loss, in addition to COP. These models allowed evolution of tank water temperature over time to be determined. The resulting simulations had acceptable errors when compared to the measured values.

It can therefore be concluded that the models developed from the AS/NZS test data give accurate predictions of the COP during the heat-up phase when the HPWH is tested under other national test standards, and thus could be used to avoid the need to carry out additional physical tests for those standards.

However there are limitations regarding:

- the simulation of “hybrid” systems (heat pumps with electric resistance elements, such as HPWH Model A), due to absence of information about the control logic used;
- the choice of regression variables used in the model; and
- the potential to model COP performance over a full test cycle including a water draw-off pattern.

Due to limitations in the experimental data used to develop the simulation method, the average tank water temperature was used for all the HPWHs tested, resulting in important errors for some operating conditions. In general variables that are better adapted to the specific configuration of the HPWH should be used, provided that appropriate experimental data are available.

Modelling performance during a full test with draw-off pattern requires a number of factors to be considered. While in principle the heat losses of the storage tank can be modelled without undue difficulty, the part-load performance of the heat pump and its control logic are unknown. Even though the proposed methodology was found to work for the HPWH Models B and C operated under the US test standard conditions, the method needs to be tested with other systems where the control logic is known in order to clarify the energy performance impact of the control logic, which may vary across different operational modes.

3.3 Summary

The physical testing program was instructive in a number of ways. It indicated the difficulty of interpreting different standards and conducting tests that were fully in accordance with them, even in an experienced and well-equipped laboratory.

The testing program confirmed the assumption that *absolute* COP (or EER) values derived from physical testing to different standards are so different that comparisons across standards are not possible. Furthermore, the *relative* rankings in apparent energy efficiency can easily reverse under different test standards.

Performance modelling also has limitations. Complex modelling (e.g. using programs such as TRNSYS)[23] requires a large amount of information, including proprietary data on the HPWH refrigeration system, which can only be obtained from the manufacturer. One objective of simpler forms of modelling is that they can be carried out solely on the basis of the data collected by testing a randomly purchased unit in a laboratory.

If sufficient data are collected on performance during the heat-up phase, it is possible to reliably simulate the performance of that HPWH during the heatup phase of other test standards, where ambient conditions, inlet water temperatures and water heater thermostat setting are different. However, this is limited to HPWHs without electric resistance elements (or where the element is disabled during the heatup phase).

However, this alone is of limited practical value, since at present there are only two published standards where the physical testing ceases after the heatup phase – the AS/NZS and Chinese standards. The Canadian/USA, European and Japanese tests all involve draw-off tests as well.

With further work, and with full data on the heat loss of the storage tank, the simulation model may be adaptable to predicting the performance of a HPWH under the physical draw-off sequences in various standards, with acceptable accuracy. It may be necessary to obtain details of the control logic, which would conflict with the objective of modelling solely on the basis of the data collected by testing a randomly purchased unit in a laboratory. Alternatively, it may be possible to devise a series of tests which reveal the main parameters of the control logic.

Modelling the performance of a hybrid HPWH while the heat pump is operating in parallel with the resistive element is even more difficult. Most difficult of all would be to model the performance under varying ambient conditions and varying load, to simulate seasonal use. To characterise load cycle operation, particularly for systems with advanced controllers, requires a transient model of stratified conditions in the tank.

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[23] TRaNsient SYstem Simulation (TRNSYS) is a public domain model originally developed by the University of Wisconsin. It is an algebraic and differential equation solver typically used to simulate performance of energy systems including water heaters, heating ventilation and cooling systems and renewable energy systems.

4. Conclusions

4.1 Comparison of Test Standards

At present, the only way to demonstrate that a given heat pump water heater complies with the MEPS, energy label ratings or other energy efficiency programs of a particular economy is to test it to using the method of test specified for that purpose.

In an ideal form of harmonisation, testing authorities in each economy would be able to take the results from any of the existing HPWH tests, and use a simulation model to predict what the results would be if the same model were physically tested to their own standard. However, this ideal is not likely to be attainable.

This is so despite the many similarities between the methods of tests currently in use. All of them are carried out in controlled ambient conditions of temperature and humidity. All involve heating the water from ‘cold’ to ‘hot’, and measuring both the electrical energy consumed by the HPWH and the thermal energy added to the water.

However, the similarities end there. The testing methods differ significantly with regard to:

- The categorisation of products by types, capacities and characteristics for the purpose of selecting the range of tests to be performed;
- The precise ambient conditions to be maintained in the test room and the variability limits permitted;
- The temperature of the inlet water and the variability limits permitted;
- The draw-off patterns;
- The methods of measuring and recording the temperature and heat content of the water in the storage tank (or in some cases, the outlet water only); and
- Whether the test covers performance during heatup only, or during physical tapping and standing heat loss as well.

There differences are detailed in Appendix A. There is no single ‘best’ test method which could be adopted for global use – all have their advantages and disadvantages.

Some are more reproducible, in that a test in a different laboratory is more likely to get the same results. In general, the test methods which specify sensor location and higher instrumentation accuracy are likely to give more reproducible results, but the tests may be more costly. The heat-up stage of testing could be specified in a way that makes it highly reproducible, provided that the ambient conditions, inlet water temperatures and in-tank temperatures are tightly controlled and monitored. The performance of heat pump water heaters is particularly sensitive to ambient conditions, so test standards which cover more conditions are likely to replicate actual use better – but the tests are more expensive to carry out.

Simple draw-off sequences (larger volumes at longer time intervals) are also fairly reproducible. There are greater difficulties in reproducing complex sequences of variable draws, especially where the signal for terminating a draw is the temperature of the flow.

It is not possible to conclude that any of the draw-off sequences in any of the existing test methods is superior to another. Some will reveal different weaknesses in the performance of the water heater (eg the ability to reheat after long draws, and whether reheating occurs at all after short draws).

Even detailed draw-off tests covering different daily loads and sequences do not necessarily replicate the hot water use of all households. Research on hot water use generally indicates that it is highly variable from one household to another, and in the same household over time. There is no standard draw-off sequence that could reliably represent hot water use in all economies, or even one economy for that matter.

At the same time, all hot water use is similar in that it consists of sequences of draws at irregular intervals and of different volumes and flow rates. Therefore measuring how a water heater performs over one sequence of tasks may allow its performance at other tasks or other ambient conditions to be calculated or modelled. While there are some demographic and climatic drivers for hot water use, there are random elements as well. It is important to consider the performance of the HPWH over the likely distribution of use, which makes specific draw-off patterns less useful, unless they are used to develop and verify a more flexible global modelling approach.

4.2 Proposed Approach to Harmonisation

Given the extent of the differences, it is not considered likely that the standards bodies and energy program regulators in different countries would agree to adopting a common standard, without a gradual process of confidence-building and harmonisation.

Although this project did not research the issue directly, the support for test harmonisation may be not be universal, or at least equally strong in all cases. There is certainly a high level of support among some global manufacturers who export widely. They have an obvious commercial interest in reducing the amount of product testing required for each market.[24] Even so, their home economies will probably wish to retain their own standards.

Manufacturers who specialise in supplying products to one national market or trade region become familiar with one particular test standard, and optimise their products to perform under that standard. They may be wary of changing local methods of test, or broadening the means of demonstrating compliance, in ways that might help importers gain market share. For some manufacturers (including global suppliers), differences in methods of test are low on their concerns. Is it of greater commercial interest that the local standards in their export markets shows their products in a good light, and that government support in those markets (eg through regulation or direct cash incentives) for favours HPWHs.

Local standards bodies and regulators also have a major investment in the existing methods of test. Although some of the standards bodies and governments of the economies with HPWH standards already in place are investigating possible changes, it is in the context of building on what they already have. The range of ambient conditions and draw-off schedules developed for different standards attempt to replicate local conditions and user behaviour (with varying degrees of success). They have also evolved to reflect the predominant types of product preferred in the local markets, and in some cases do not cover the testing of other configurations.

Recent developments seem to be moving in the direction of greater elaboration and difference rather than simplicity and convergence, e.g.:

- The intended introduction of a new draw-off test in AS/NZS 5125 in Australia and New Zealand;
- The proposal to introduce a pattern of variable task-simulation drawoffs in place of the existing equal and evenly spaced drawoffs to the USA CFR 430 test;
- The development of a new Republic of Korea test standard, which is likely to differ from all the existing test standards (while having some common features); and
- The development of an entirely new ISO test standard.

While proliferation may at first appear to inhibit harmonisation, there are also opportunities for promoting it, should the stakeholders wish to go in that direction.

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[24] In a presentation to the Beijing workshop for this project, representatives of Haier Water Heater Division pointed out that the average time for certification of a product to EN 16147 in Europe was 3 months, and the cost was 50,000 Euros per product series. Haier alone produces more than 10 series and 30 separate models.

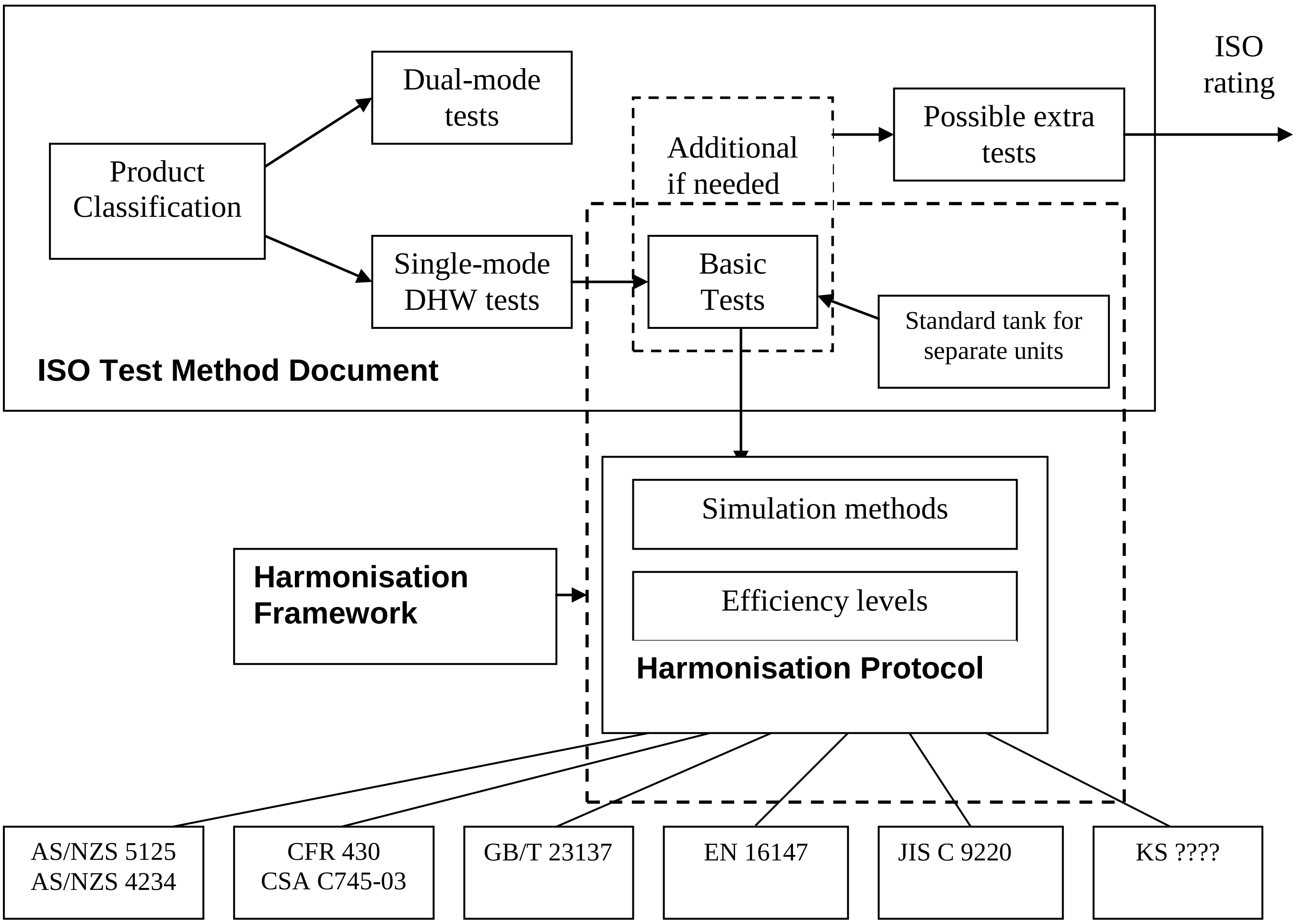
4.2.1 Harmonisation Framework

If there were no existing standards for HPWHs, then the development of an international standard would itself constitute a sufficient focus and stimulus for harmonisation. In this case, even though there are six different families of existing standards, the initiation of work on an ISO test provides the opportunity to establish such a framework.

Figure 4 illustrates the key elements of such a framework. Their suggested grouping into specific documents is indicative only. Furthermore, if the ISO does not wish to become involved in such a harmonisation process it could be managed through the IEC (if willing) or in other ways.

The first element is a Standard Product Classification. A common language and product typology which classifies all current HPWH types and configurations in a consistent manner is a pre-requisite for the development of a harmonised testing approach. Table 7 gives an example of how this might done. The proposed ISO test standard would be an obvious document in which to include such a typology – even if the ISO test standard restricts itself to coverage of only some of the defined product categories.

Figure 4 Diagram of possible harmonisation framework



It is understood that ISO Technical Committee C86/SC6, which will be developing the HPWH test, is yet to decide whether to only cover the testing of HPWHs serving a Domestic Hot Water task only (“single mode DHW testing”), or also those capable of serving a space heating task as well – either while in one or other mode, or both modes simultaneously. At present only European EN 16147 and the draft KS standard refer to the possibility of dual-mode HPWHs, and EN16147 only provides for the testing of such units in DHW mode. This provides an opportunity for the ISO to develop both a single mode Space Heating test, and a dual-model test, and have them adopted as default international tests.

For single mode DWH testing, the key to harmonisation is a set of basic tests, which might be similar (but not identical) to the most common test conditions currently in use (see Table 8):

- A low-temperature test condition of 7°C DB/6°C WB – this is already included in the European, Japan and Korea (draft) standards, and would be consistent with one of the conditions in the AS/NZS standard (<10°C);
- A water temperature of 10°C for the above test;
- A warm-temperature test condition of 20°C DB/19°C WB – this is already included in the USA, Canada, and China tests, and would be consistent with one of the conditions in the AS/NZS standard (18-20°C);
- A water temperature of 15°C for the above test;
- For models designated as suitable for use in frost conditions, a test at 2°C DB/1°C WB (this designation should be part of the Product Classification system);
- For models designated as suitable for warm and humid climate conditions, a test at about 30°C and high humidity.

No draw-off test would be necessary at the above test conditions – only a heat-up test and either a static operation test (in which the compressor is allowed to run to cover heat loss from the tank) or a cool-down test (in which the compressor is switched off and the tank allowed to cool).

The ISO could of course include additional basic tests, including safety, as well as draw-off tests or other tests to support whatever approach it desired to take.

One aspect of the basic test conditions would be the specification of the storage tank to be used with stand-alone (‘separate’) heat pumps, in the absence of a clear direction from the manufacturer. As tank volume, shape, heat loss and inlet and outlet positions can all affect HPWH performance, it would be crucial to define one or more ‘calibrated standard reference tanks’. These could be actual nominated models, analogous to the ‘reference models’ used in some other product test standards. Over time all test laboratories involved in HPWH testing would acquire reference tanks.

The data from the basic test would be used in a simulation method, which could be developed as part of the ISO test or as a separate document. The product parameters would be entered into a model. To the extent that this method required information about a HPWH’s refrigeration system or control strategy, it would be restricted to data that could be observed or established through physical tests (which would form part of the basic test suite for certain product types). More complex modelling options may also be included.

The immediate purpose of the Harmonisation Protocol would be to establish how a HPWH for which the Basic Tests had been conducted to the (new) ISO standard would rate under each of the 6 existing standards, without doing additional physical testing. It may also be useful to also establish equivalence between the six tests and a full ISO rating, but it may be unnecessary. If the ISO test standard is structured as proposed in Figure 4 then every HPWH tested to the ISO standard will have gone through the Basic Tests, and that data should be available.

Once workable simulation methods are developed and accepted, the next step would be to determine sets of HPWH efficiency levels applying to different Product Classifications. The lowest efficiency level allowed under any of the six existing standards or in any of the economies using those standards could be Efficiency Level 1 (EL 1). This would be translated into the COP, EER or other values determined under each standard. For example, EL1 for unitary systems might be equivalent to, say, a COP of 1.8 on EN 16147, an EER of 2.0 on CFR 430, a COP of 2.1 on GB/T 23137, and so on. Higher ELs could also be defined over time, perhaps with EL4 equivalent to the most efficient currently on the market, so that EL5 and EL6 are reserved for future improvements. Over time, national energy efficiency programs for HPWHs could refer to the standard ELs when setting MEPS levels, in the same way as MEPS programs for electric motors do now.

4.2.2 Modelling and Simulation

Considerable work remains to be done to develop Simulation Methods of acceptable accuracy. Some of the issue to be addressed are identified in Appendix C, though as this analysis is based on only a handful of physical tests, the findings are only preliminary.

Without some form of simulation or modelling there is no realistic prospect of harmonisation short of all stakeholders agreeing to abandon their current standards in favour of the yet-to-be developed ISO test, which is highly unlikely.

Simple simulation methods may be adequate for some types of HPWHs, and for replicating some of the test procedures. More complex methods would be required for other types and other standards.

It may be advisable to develop the methods in the following stages:

1. A method that is capable of using the Basic Test data for a simple HPWH (without a heating element and not intended for use in frost-prone areas) to simulate its performance under standards which require heat-up tests only: ie Chinese standard GB/T 23137 and all four test conditions in the current AS/NZS 5125. This would allow a primary assessment of whether that unit meets the MEPS levels in GB/T 23137, and might also allow the unit to be rated to AS/NZS4234, which relies on AS/NZS 5125 outputs. However, the AS/NZS 4234 rating method uses TRNSYS, for which proprietary data would be required. The main beneficiaries of this first stage would be manufacturers who needed to have units rated to both the (new) ISO test and GB/T 23137.

2. A method that is capable of using the Basic Test data together with a more complex simulation method (but not requiring proprietary information to be supplied by the manufacturer) to model energy use for the standard drawoff regimes included in all HPWH standards now in use.

3. A method that is capable of using the Basic Test data together with proprietary information on the refrigeration cycle and control strategies, to model performance under any ambient conditions and any draw-off cycles, not just those in the existing test standards. (This is the approach currently used in Australia and New Zealand. The physical characteristics of the HPWH are measured using AS/NZS 5125, which has no draw-off tests. The annual energy use is then modelled, using a computer simulation program which meets the criteria in AS/NZS 4234. The best known of these programs is TRNSYS, although others may be used).

The need for proprietary information in Stage 3 raises a number of issues for compliance check tests, especially those done outside the economy of manufacture:

- It can introduce delays in contacting the manufacturer, requesting and obtaining the necessary information;
- The manufacturer may choose to withhold the information in order to delay the testing process; and
- It has been found that the information provide (eg on control settings) is sometimes inconsistent with the observed behaviour of the unit in the laboratory.

However, if it is in the interests of manufacturers to use the harmonisation process to save testing effort, it will be in their interest to volunteer accurate proprietary information to make it work.

As performance under frosting conditions is nearly impossible to model, there will probably have to be a separate physical test for units intended for use in frost-prone climates.

This approach would have to exclude conditions where the heat pump supplies a space heating load as well as a domestic hot water load, since it is very difficult to standardise the magnitude of a combined load, or how it would vary in actual use (e.g. it may be better to switch off the HPWH altogether over summer and get the domestic hot water either by a resistance element or some other way - or switch the water loop so it bypasses the space heating load heat exchangers, in which case it becomes a pure domestic water heater).

4.2.3 Harmonisation Protocol

The elements described above constitute what may be termed a ‘Harmonisation Protocol’ – a set of technical standards, agreements and working arrangements to cover both administrative and technical matters as they arise. Clearly, the protocol would have to involve HPWH manufacturers, energy policy and program agencies, standards bodies and technical experts.

The documentation of the protocol may be embodied in a single standard or, more likely, a number of related standards. There are a number of international agencies and frameworks that could host or support the development of the protocol, including the ISO, the IEC or some of the sponsors of the present report: CLASP, the Asia-Pacific Economic Cooperation (APEC) Collaborative Assessment of Standards and Testing Methods (CAST) initiative. and the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative of the Clean Energy Ministerial.

One way of building global confidence in a harmonisation protocol it would be to adopt it as a screening test in the first instance. A manufacturer exporting to another economy could offer the results of the Basic Tests and the simulation results as a means of demonstrating compliance with the necessary requirements. If a subsequent check test using the standard of the importing economy found that a unit matched the performance which had been determined under the modelling (within stated variances) then the original result would be validated.

If the check test found that the unit did not match the claimed performance, there may be two reasons for this.

- The unit performed differently under the basic physical tests than claimed by the supplier. These tests could then be repeated to see if this is cause of the inconsistency, and if so it could be due to some manufacturing variance or fault, which the supplier could address; or
- The unit performs as claimed on the basic physical test. If so, and the modelling method was correctly applied, it must have failed to account for some aspect of the unit's performance, and so was invalid in this case. The manufacturer should then be given the option of undertaking a full test to the standard of the importing economy, to adjust the performance claims accordingly and, if necessary remove the product from that market if it fails to meet the local MEPS.

4.3 Next Steps

This report marks the completion of the present project. Its original objectives were to analyse current standards and test methods to evaluate the energy efficiency of heat pump water heaters, and to prepare proposals for internationally-comparable energy efficiency test methods, metrics and efficiency levels, for use in future efficiency policy measures.

There is considerable work to be done before internationally-comparable energy efficiency test methods, metrics and efficiency levels are at a stage where they can be used in future efficiency policy measures. A harmonisation framework is proposed for this purpose, including standardised physical tests and a staged development of simulation methods.

The impending development of an ISO test method for heat pump water heaters offers a timely opportunity to make a start on a harmonisation framework (provided the ISO consider this a priority). However, there are other ways and possible for a to address the issues.

If the ISO is not considered the most suitable forum, than alternative fora may be:

- The IEC, which already sets some standards for electric water heaters (but not those for heat pump technology). The IEC, like the ISO, has broad membership;
- APEC/CAST - however, this is a largely a government level structure (without direct manufacturer engagement) and the EU is not a member;
- SEAD – again, this is largely a government level structure, and China is not a member; or
- A completely new project framework, which would take some time to set up and would divert resources from other work.

It is up to the stakeholders – manufacturers, energy policy and program agencies, standards bodies and technical experts – to decide how to proceed.

We suggest the following stages:

1. This report should be sent to all the relevant standards committees and government agencies responsible for HPWH test standards, to seek their indication of:
   - whether they support the development of a Harmonisation Framework, along the lines proposed in Figure 4, and if so:
   - where the work should be located (e.g. ISO or some other forum);
   - whether and how they wish to participate; and
   - whether they are willing to contribute resources (e.g. to support the funding of experts or product testing) to expedite the standard development process.

2. If there are sufficient favourable responses, seek an indication from ISO (or IEC, APEC/CAST or SEAD) that they are willing to host or otherwise support the harmonisation project.

3. Once a project is established, the work program could be structured as follows:
   - reach an outline agreement on a harmonisation protocol;
   - develop the Basic Test conditions (along the lines proposed in this report);
   - undertake round-robin testing (in at least three laboratories) of a number of HPWH units (say 6 to 10) of different configurations, testing the units to the Basic Test conditions (i.e. expanding on the KTL work for this project);
   - analyse the test results and develop a simulation model, based on parameters that can be established in laboratory testing (i.e. without relying in proprietary data);
   - validate the simulation model with the original tested units;
   - undertake a wider validation program with other willing participants (manufacturers, standards bodies and other agencies); and
   - incorporate the final method of test and simulation method in one or more standards or other published documents.

In the meantime, economies that wish to formally adopt a method of test for HPWHs, but have not already done so, should consider selecting one of the existing test methods, rather than developing a new one.

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References

Standards

Australia & New Zealand

AS/NZS 5125.1:2010 *Heat Pump Water Heaters – Performance Assessment*

AS/NZS 4234:2008 *Heated water systems - calculation of energy consumption*

AS/NZS 4692.1:2005 *Electric water heaters - energy consumption, performance and general requirements*

Canada

CAN/CSA C745-03:2003 *Energy efficiency of electric storage tank water heaters and heat pump water heaters-Third edition Update No1: 3/2005*

China

GB/T 23137–2008, *Heat Pump Water Heater for Household and Similar Uses*

GB/T 21362–2008, *Heat Pump Water Heater for Commercial & Industrial and Similar Uses*

Europe

EN 16147:2011 *Heat pumps with electrically driven compressors - Testing and requirements for marking of domestic hot water units*

Japan

JIS C 9220:2011 *Residential Heat Pump Water Heaters*

Korea

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Appendix A: Summary of key test standards

Table 7 Terminology for product configurations

	Configuration	**Australia & NZ** AS/NZS5125	**USA** CFR430	**Canada** CSA-C745-03	**China** GB/T23137/21362	**Europe** EN16147	**Japan** JISC9220-2011	**Korea** Draft (KSB ****)
1	HP and tank in same casing (a) – location of installation not specified	Integral	Heat pump water heater with storage tank – integral	Not directly defined, but test accommodates	Packaged type	ND	Single package	Single package
2	HP and tank in same casing – indoor tank location	ND	ND	ND	ND	Factory-made units which can be ducted on airside	ND	ND
3	HP and tank separate but supplied together – linked by water lines	ND	Heat pump water heater with storage tank – separated	ND	Split type	ND		Split type
4	HP and tank separate but supplied together, linked by refrigerant lines	Integral (‘condenser integral to tank’)	Heat pump water heater with storage tank – separated	ND	Split type	Split Heat Pump – outdoor heat exchange	Split	Split
5	HP sold separately – may be linked to any storage tank by water lines	Stand-alone heat pump	HPWH without storage tank (also called ‘Add-on’)	Not directly defined, but test accommodates	Not directly defined, but test accommodates	ND	Split	Split
6	Recirculating stand-alone heat pump	Requires recirculation to reach final storage temp.	ND	ND	Circulated heating HPWH	ND		ND
7	Once-through stand-alone heat pump	Delivers water at final storage temp in one pass	ND	ND	One-time heating HPWH	ND		ND
8	Static heating HPWH	ND, but probably all of types 1-5	ND, but probably all of types 1-5	ND, but probably all of types 1-5	Water flows past heat exchanger by natural convection	ND		ND
9	Off-peak product	ND	ND	ND	ND	Meets load without external energy supply 0700 to 2200	Meets load without external energy supply 0700 to 2200	ND
10	Ability to heat water for hydronic space heating	No	No	No	No	Possible but only domestic hot water production tested	ND	Possible but only domestic hot water production tested
11	Special configurations or designations	Suitable for low ambient temperature without boosting	ND	ND	ND	With ‘smart control’ to adapt to individual usage conditions	With ‘Intermediate holding tank’ for bath recirculation	ND

ND = Not specifically defined in this standard, but not necessarily excluded. (a) Refrigerant condenser may be in or on the tank, or there may be separated by water circulation lines but within the same casing.

Table 8 Summary of Test Conditions for Heat Pump Water Heater Test Methods

Parameters	**Australia & NZ** AS/NZS5125	**Australia & NZ** AS/NZS5125 draft revision	**USA,** CFR 430 **Canada** CSA-C745-03	**China** GB/T23137/21362	**Europe** EN16147	**Japan** JISC9220-2011	**Korea** Draft (KS B ****)
Scope (brief)	Heat pump (air source)	Heat pump (air source)	Electric storage 76L to 454L, Heat pump to 24A single phase 250V	23137 – domestic 21362 – comm./ind Air and water source	Heat Pump – air water or brine source, domestic HW only	Household air source heat pump (HFC or CO_2) with tank	Air source heat pumps for hot water and space heating, with or W/O tank
Test Chamber	Wooden platform and walls	Wooden platform and walls	Wooden platform and walls	Not stated	Avoid direct radiation	Insulated chamber (calorimeter)	Insulated chamber (calorimeter)
Ambient Air Test Conditions (TC)	TC1 <10°C TC1 80% to 90% RH TC2 18°C to 20°C TC2 60% to 70% RH TC3 30°C to 35°C TC3 30% to 40% RH TC4 30°C to 35°C TC4 55% to 65% RH Low temperature (LT) for products claimed suitable for low temperatures 0°C to 2°C, RH >= 90%	TC2 18°C to 20°C TC2 60% to 70% RH Low temperature A for models suitable for low temp zones without boosting 0°C to 2°C, RH >= 90% Low temperature B for models where boosting needed for low temp zones 6°C to 8°, RH 80-90%	19.7°C ±0.5°C (67.5°F) 49% to 51% RH	Nominal 20°C ±.0.5°C ** WB 15°C (RH 59% @ 20°C) Maximum DB 43°C WB 26°C Auto-defrost DB 2°C WB 1°C Low temperature DB -7°C WB -8°C Variable	Evaporator 7°C WB 6°C (RH 86.8%) Tank (indoor) 20°C	TC1 (mid season) DB 16°C ± 1K WB 12°C ± 0.5K TC2 (summer) DB 25°C ± 1K WB 21°C ± 0.5K TC3 (winter) DB 7°C ± 1K WB 6°C ± 0.5K	Standard DB 7°C WB 6°C Severe Cold Zone DB -15°C WB NS
Air flow	0.25 to 0.5 m/s	0.25 to 0.5 m/s	Not stated	< 0.5 m/s	< 1.5 m/s	Not stated	ISO5151 Annex A/C/D
Cold Water Supply	TC1, LT <10°C TC2 <15°C TC3, TC4 <25°C	TC2, 13-15 °C Low temp tests 8-10 °C	14.4°C±1°C (58°F)	15°C ±.0.5°C Nom 29°C Max 9°C Others	10°C ±0.20K	TC1 17°C ± 2K TC2 24°C ± 2K TC3 9°C ± 2K	Low 15°C±0.15 K Midum 30°C±0.15 K High 40°C±0.15 K
Thermostat setting for test	Maximum	Maximum	57.3°C ±3K (135°F ±5°F)	55°C ±0.5°C	Nominally 55°C (temperature rise 45K)	Normal ≤65°C (Winter hot >65°C) (Sanitary = max)	Manufacturer's instructions (nominal 50°C)
Water Pressure	Not specified	Not specified	275kPa to rated	Not specified	Not specified		≤ 343 kPa
Installation	Manufacturer's instructions. Piping be as short as	Manufacturer's instructions. Piping be as short as	Installed in accordance with manufacturer's	Installed in accordance with manufacturer's	Installed in accordance with manufacturer's	Installed in accordance with manufacturer's instructions.	Installed in accordance with manufacturer's

Parameters	**Australia & NZ** AS/NZS5125	**Australia & NZ** AS/NZS5125 draft revision	**USA,** CFR 430 **Canada** CSA-C745-03	**China** GB/T23137/21362	**Europe** EN16147	**Japan** JISC9220-2011	**Korea** Draft (KS B ****)
	practicable (where applicable)	practicable (where applicable)	instructions.	instructions.	instructions (excluding optional accessories).		instructions.
Tanks Sensors	6 equal volumes	6 equal volumes	6 equal volumes	Not specified	Not specified #	Inlet and outlet only #	Inlet and outlet only
Daily Drawoff Volume	None (heat up only)	Varies (specified as energy content)	243.4L	None (heat up only)	5 from S=36L to XXL=420L ***	Standard 455.7 L (40°C) Small 278.0 L (40°C)	None
Daily Drawoff Pattern	No physical tests (a) seasonal modelling		6 × 40.6L at 1h	None	Complex (24 hour) (11 to 30)	Complex (24 hour) (51 and 31)	None
Drawoff energy	No physical tests – seasonal modelling		43.7 MJ	Not applicable	7.5MJ to 87.9MJ	See separate table	Not applicable
Drawoff Flow rate	Not applicable	9 kg/min ±0.5 kg/min	11.4 L/min	Not applicable	4 or 10 L/min	5 or 10 L/min	Not applicable
Heat Loss	AS/NZS4692.1		Standby part of test	Test Method for Thermal Insulation Performance (heat and cool down)	Not directly measured, but included in standby power input	To be confirmed	Not directly measured
Performance tests included	Low ambient temperature performance		First hour rating (volume for temperature drop of 13.9K) Volume	Max operating Auto-defrost Min operating Low temperature Design and construction Noise Volume for 10K drop	Heat up test Standby power (heat loss) Max temp and hot water delivery (40°C) Operating range Safety	Safety Various performance Design and construction	Safety Material Structure Performance for Space heating Performance for sanitary water supply Seasonal COP Noise
Test Point Period	Consists of the period of time where the mass weighted average tank temperature changes by 5 K to 5.5 K		Water draw off with normal water heater operation until the heat source cuts in, stop the draw and wait until the maximum mean tank temperature is achieved				

NS = not specified. # In some cases, sensors are located at 40mm spacing to calculate residual heat. (a) A revision of the test standard is under way. It is planned to include draw-off tests for the purpose of determining minimum energy performance (MEPS) levels.

Some of these heat pump test methods appear to draw on air conditioner test methods such as ISO5151. Some specify a calorimeter for testing. The air temperatures are similar to some air conditioner temperatures (eg GB/T (China) and USA ambient conditions are similar to ISO5151 indoor heating (and outdoor minimum cooling), EN (Europe) and JIS are the same as ISO5151 H1 outdoor heating conditions, Korea Low temperature and Cold Zone ambient temperatures for space heating tests are the same as ISO5151 outdoor heating conditions (H2 and H3 respectively).

** Under GB/T23137 heat pump water heaters with CO_2 refrigerant have different operating conditions as follows:

- Inlet water 17°C ±1K
- Outlet water 65°C ±2K
- Air dry bulb 16°C ±1K, air web bulb 12°C ±0.5K (RH=62.8%)
- Additional safety and construction requirements are included.

*** In EN16147, there are several drawoff patterns (called tappings) as follows:

- There are about 10 different drawoff event types specified, each with its own energy drawoff and flowrate (4 or 10 L/s)
- There are 5 drawoff patters described: Small, Medium, Large, X Large and XX Large made up of standard events
- Small – 11 events, 2.1 kWh (7.56 MJ), nominally 36 litres at 60°C equivalent
- Medium – 23 events, 5.845 kWh (21 MJ), nominally 100.2 litres at 60°C equivalent
- Large – 24 events, 11.655 kWh (41.96 MJ), nominally 199.8 litres at 60°C equivalent
- X Large – 30 events, 19.07 kWh (68.65 MJ), nominally 325 litres at 60°C equivalent
- XX Large – 30 events, 24.53 kWh (88.31 MJ), nominally 420 litres at 60°C equivalent
- For many of the event types, volume delivered is not counted until a specified temperature rise is reached.

For JIS C 9220-2011, there is a series of complex drawoff patterns as follows:

- Hot water delivery temperatures are specified as 40°C -2K +0K (even though storage temperature is higher)
- There are 4 different drawoff types: wash basin, kitchen, bath, shower.
- Flow rates for wash basin and kitchen is 5L/min. Flow rates for bath are 10-15L/min and shower is 10L/min.
- Wash basin and kitchen events are generally less than 5L, a few to 25L, shower 20L or 50L, bath 180L
- Standard household and Small household profiles are specified by 3 seasons
- Standard winter - 51 events, 16.276 kWh (58.594 MJ), nominally 455.74 litres at 40°C equivalent (cold water 9°C)
- Standard intermediate - 51 events, 12.076 kWh (43.473 MJ), nominally 455.74 litres at 40°C equivalent (cold water 17°C)
- Standard summer - 51 events, 8.401 kWh (30.242 MJ), nominally 455.74 litres at 40°C equivalent (cold water 24°C)
- Small winter - 31 events, 9.927 kWh (35.737 MJ), nominally 277.96 litres at 40°C equivalent (cold water 9°C)
- Small intermediate - 31 events, 7.365 kWh (26.515 MJ), nominally 277.96 litres at 40°C equivalent (cold water 17°C)
- Small summer - 31 events, 5.124 kWh (18.445 MJ), nominally 277.96 litres at 40°C equivalent (cold water 24°C)
- Some systems have a heat exchange facility that allows reheating of bath water – for these types, some heat exchange load is added onto the based events specified.

Korean standard has additional outdoor conditions for testing for space heating to evaluate SCOP (seasonal coefficient of performance):

- Standard DB 7°C and WB 6°C, hot water inlet 40°C (loop), outlet 45°C (same as hot water production except 15°C inlet, 50°C outlet).
- Low temperature DB 2°C and WB 1°C, hot water inlet 40°C (loop), outlet 45°C.
- Cold Zone DB -7°C and WB -8°C, hot water inlet 40°C (loop), outlet 45°C.
- Severe Cold Zone DB -15°C and WB N/S, hot water inlet 40°C (loop), outlet 45°C (same as hot water production except 50°C outlet (inlet temperature under consideration)).

Table 9 Draw-off schedules

Standard	**Number of schedules, names**	**Number of Draws**	**Daily load KWh/day in hot water**	**Daily load MJ/day in hot water**	**Average MJ/draw**	**Annual load GJ/yr in hot water**	**Supply temp limits (below which draw discarded)**
Australia & NZ AS/NZS 5125:2011	N/A (a)	N/A	N/A	N/A	N/A	Modelled	N/A
AS/NZS 5125 draft revision	Small. Medium, Large	8	6.25 to 15.8	22.5 to 57	2.8 to 7.1	6.7 to 20.8	45°C
AS/NZS 4234	Small. Medium, Large	8	6.25 to 15.8 varies with season	22.5 to 57 peak winter, varies with season	Varies with season	Modelled	45°C
Canada CSA C745-03:2003	1	6	12.1	43.7	7.28	15.95	
China GB/T 23137–2008	N/A	N/A	N/A	N/A	N/A		N/A
China GB/T 21362–2008	N/A	N/A	N/A	N/A	N/A		N/A
Europe EN 16147:2011	S	11	2.10	7.56	0.69	2.76	N/A
	M	23	5.85	21.15	0.92	7.72	N/A
	L	24	11.66	41.95	1.75	15.31	N/A
	XL	30	19.07	68.65	2.29	25.06	N/A
	XXL	30	24.53	87.55	2.92	31.96	N/A
Japan JIS C 9220:2011	Std Winter	51 (56) *	16.276	58.594 (62.714)	1.149	Complex seasonal calculation interpolating measured values and specified days at 1K temperature increments	40°C
	Std Intermediate	51 (56) *	12.076	43.473 (46.533)	0.852		
	Std Summer	51 (56) *	8.401	30.242 (32.103)	0.593		
	Small Winter	31 (34) *	9.927	35.737 (37.471)	1.153		
	Small Intermediate	31 (34) *	7.365	26.515 (27.799)	0.855		
	Small Summer	31 (34) *	5.124	18.445 (19.221)	0.595		
Republic of Korea Under development	N/A	N/A	N/A	N/A	N/A		N/A
USA CFR-430	1	6	12.1	43.7	7.28	15.95	Draw terminates when temp falls by 13.9°C from nominal storage temp of 57.2°C (ie to 43.3°C)

* JIS C9220-2011 specifies some additional events associated with a heat exchange facility to reheat bath water. These events and the energy associated with them have been included in the total values shown in brackets. (a) A revision of the test standard is under way. It is planned to include draw-off tests for the purpose of determining minimum energy performance (MEPS) levels.

Appendix B: KTL Tests

The three units tested by KTL, Models A (unitary) and Model B and Model C (stand-alone units connected to a 200 litres tank) are shown below. The details of each model are given in Table 5, and the details of each test procedure are given in Table 8 and Table 9. Only one of the four test conditions of AS/NZS 5125 is illustrated; the others give similar performance curves.

In each diagram the horizontal axis represents the time duration of the test. The red line indicates the average temperature of the water in the tank. The blue line indicates the electric power use of the HPWH (the units are on opposite axes).

In Model A, which has an electric resistance element, the high power use at the beginning of the heat-up cycle is clearly apparent.

Figure 5 Photographs of tested models A, B and C

Figure 6 Model A - AS/NZS 5125, Test Condition 1

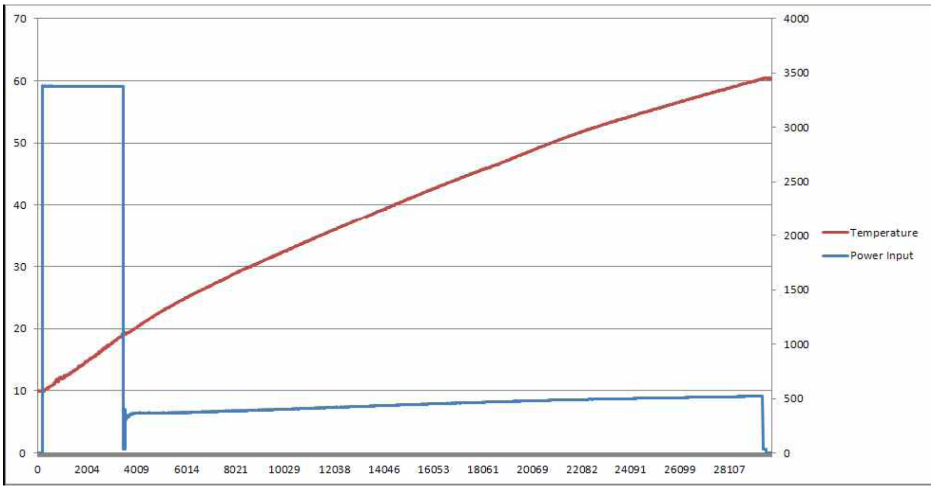


Figure 7 Model B - AS/NZS 5125, Test Condition 1

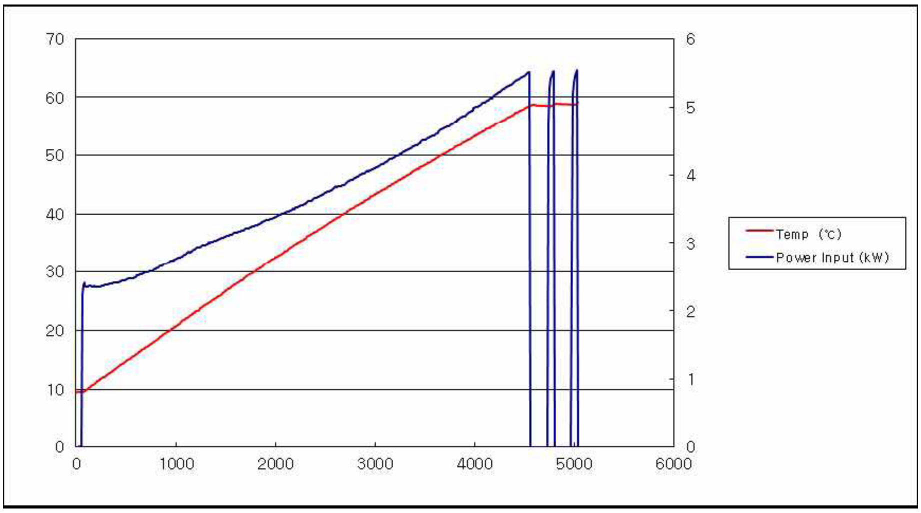


Figure 8 Model C - AS/NZS 5125, Test Condition 1

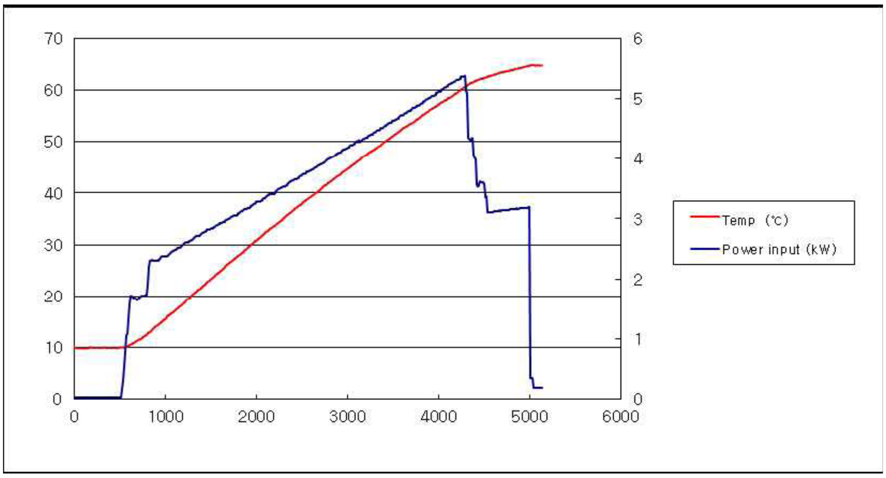


Figure 9 Model A - US CFR 430 Test

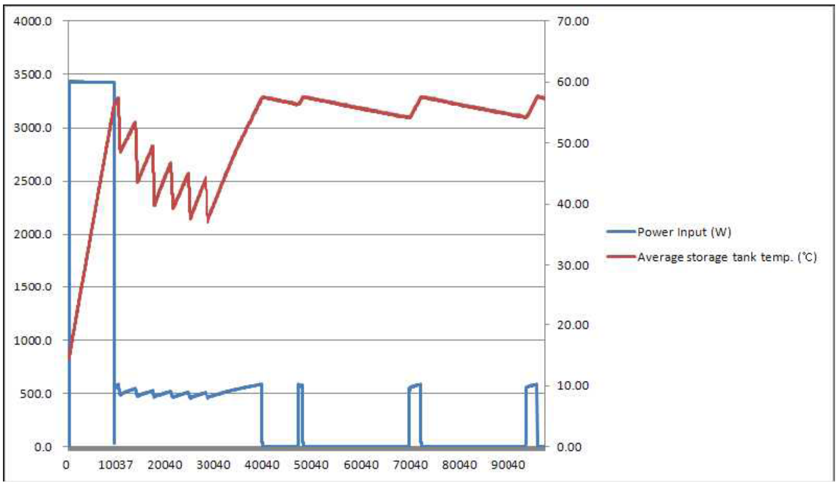


Figure 10 Model B - US CFR 430 Test

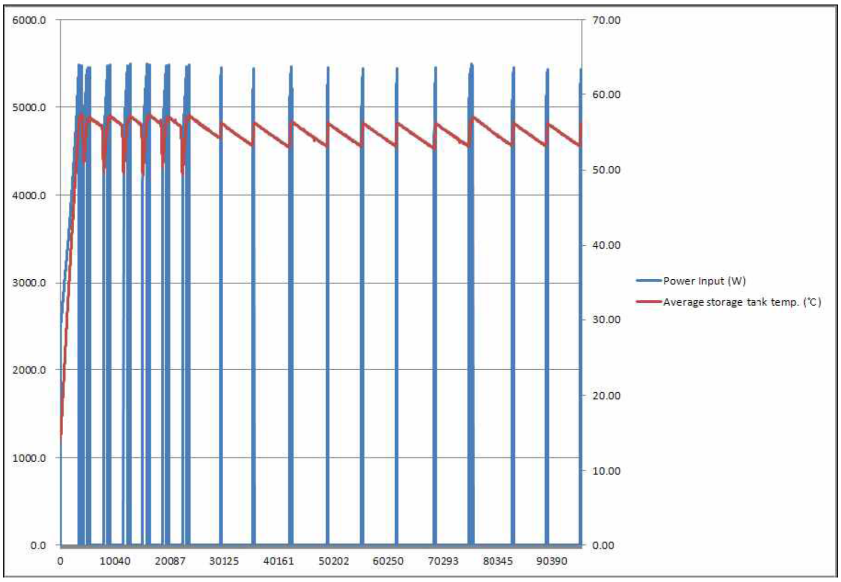


Figure 11 Model C - US CFR 430 Test

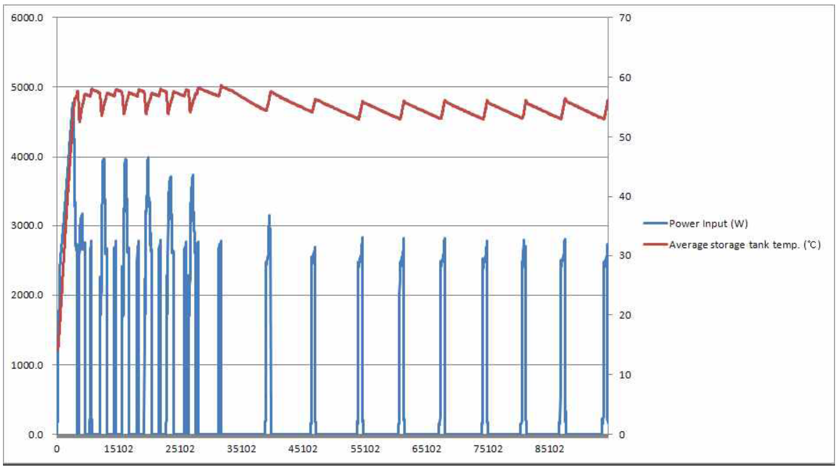


Figure 12 Model A - JIS C 9220 Test

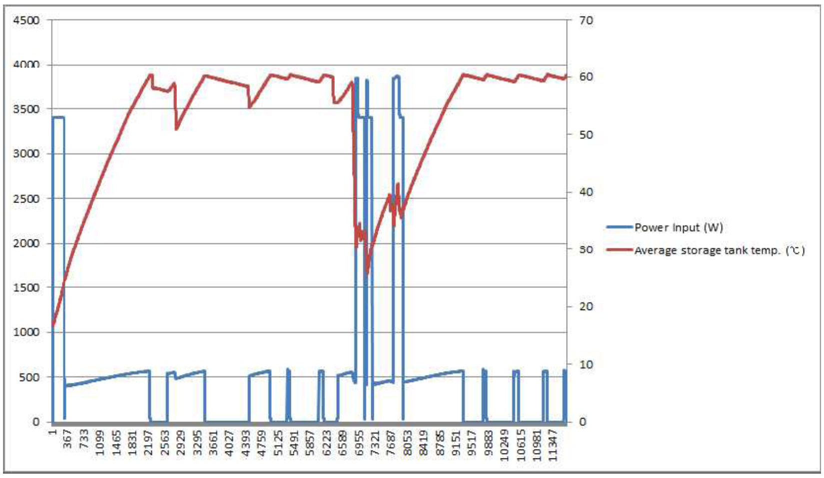


Figure 13 Model B - JIS C 9220 Test

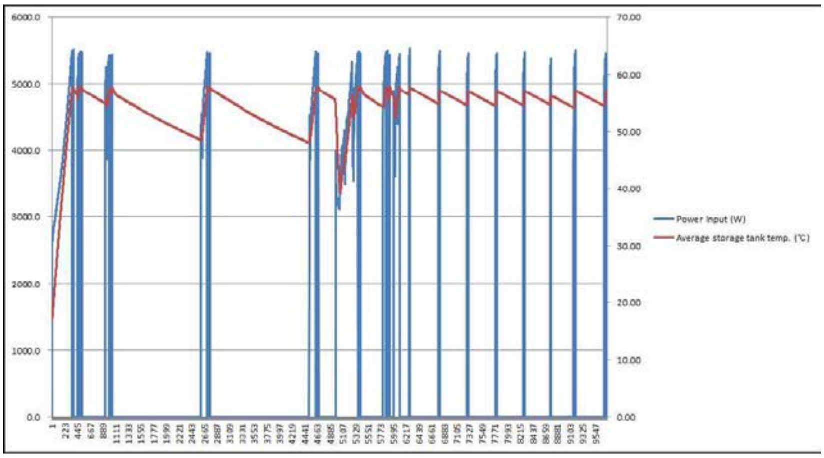


Figure 14 Model C - JIS C 9220 Test

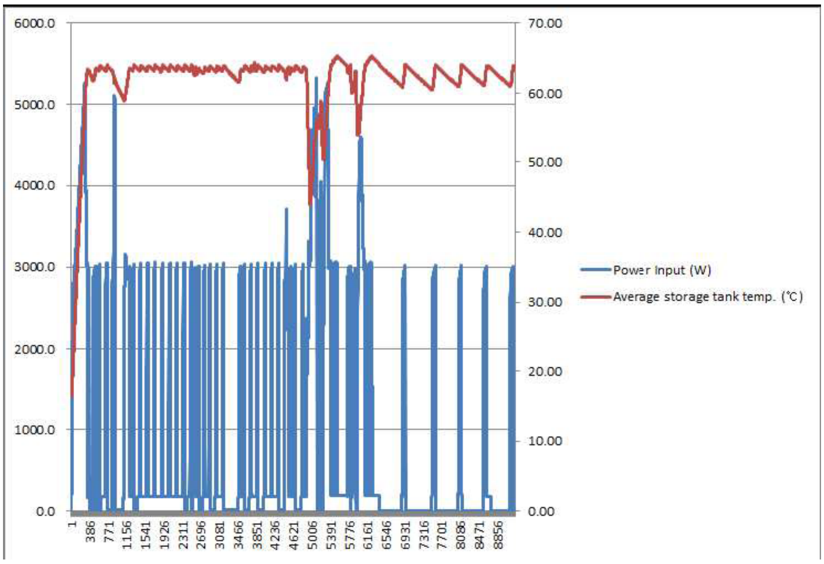


Figure 15 Model A – EN16147

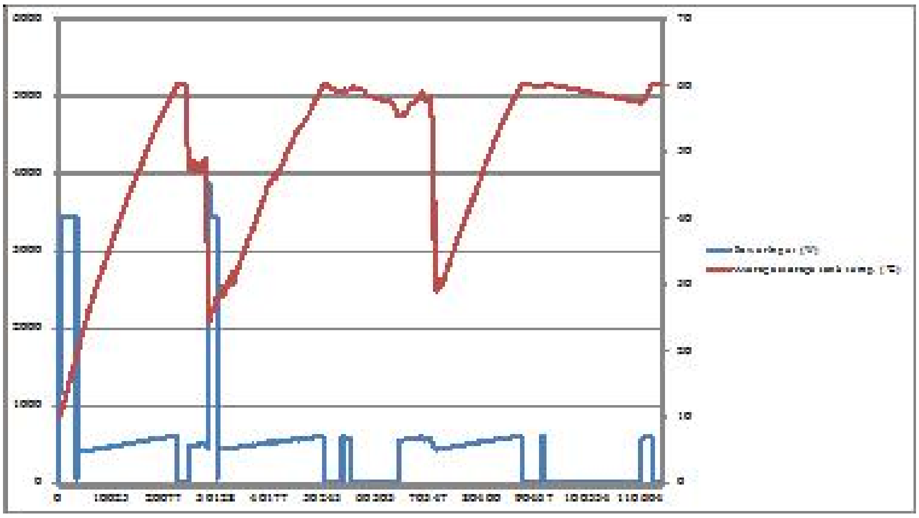


Figure 16 Model B – EN16147

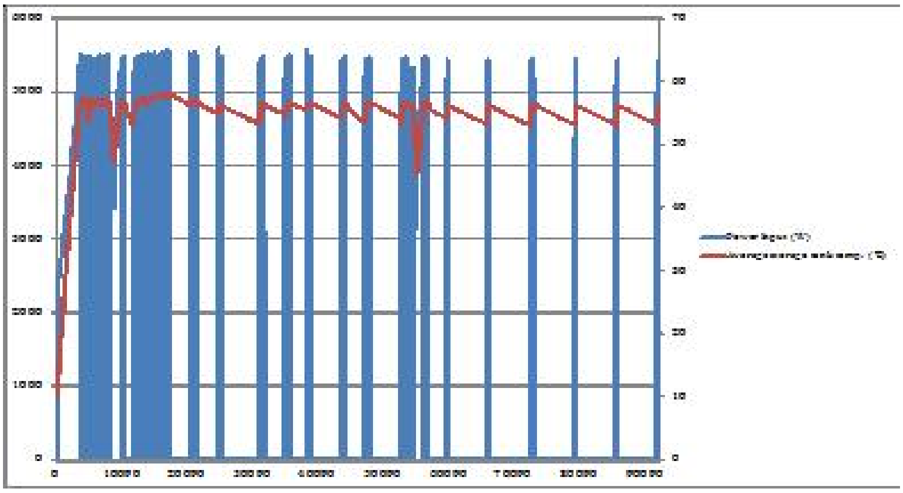
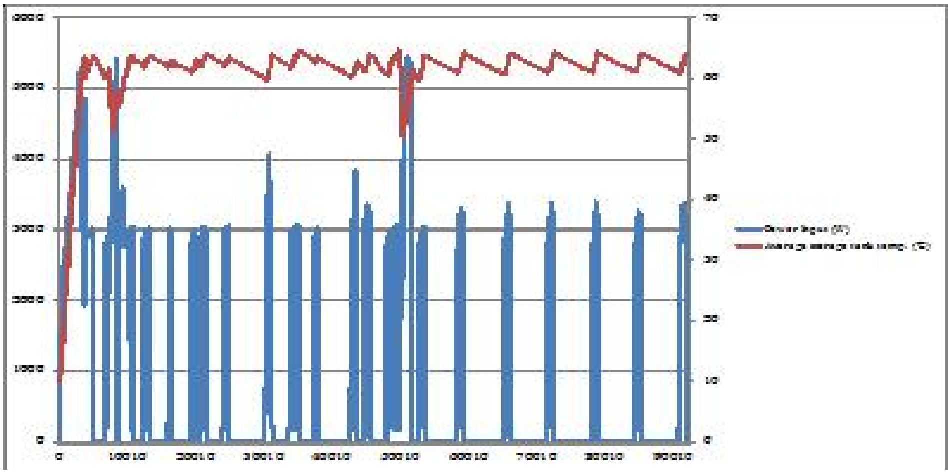


Figure 17 Model C – EN16147



Appendix C: Energy performance modelling of Heat Pump Water Heaters

Nomenclature

Nomenclature			**Subscripts**	
c_p	heat capacity	J/kg. °C	a	air
m	water mass	kg	d	dry-bulb
$\dot{Q}$	heating power	W	dew	dew point
T	temperature	°C	f	final moment
$\dot{W}$	electric power	W	i	initial moment
K	Temperature in Kelvin	K	ins	instantaneous value
ε	Error	%	int	integrated value
			t	tank
Abbreviations			w	water

C1. Introduction

This report addresses the simulation of the energy performance of heat pump water heaters. The objective is to explore how heat pump water heater (HPWH) energy performance can be simulated from a limited set of physical standard test data in order to enable the comparison of test results in different economies and to limit the time and testing costs required by standards and labelling programmes.

The principles of HPWH operation are well understood and some existing models allow HPWH performance to be accurately simulated. However, these models are relatively sophisticated, require significant input data and thus are difficult to use in a regulatory environment.

In this context, the objective of the current work is to study the possibility of developing a simplified performance model built from a number of experimental test results and then to examine the predictive capability of the model developed.

C2. Proposed approach

HPWH simulation fundamentals

Under steady-state working conditions, the instantaneous coefficient of performance is defined as the ratio of the heating power produced by the HPWH $\dot{Q}$ and the electric power $\dot{W}$, where:

$$COP_{ins} = \frac{\dot{Q}}{\dot{W}} \qquad \textbf{Eq. 1}$$

In general, COP_{ins} depends mainly on the operating conditions, including the ambient temperature and the water temperature. During a standard performance test, the ambient temperature is set to be constant but the tank temperature varies. In this situation, the coefficient of performance is defined by integration over the test duration:

$$COP_{int} = \frac{\int_{t_i}^{t_f} \dot{Q} dt}{\int_{t_i}^{t_f} \dot{W} dt} \qquad \textbf{Eq. 2}$$

where the subscripts *int*, *i* and *f* refer to integrated, initial moment and final moment respectively.

If the heat-up phase without a draw off cycle is considered in isolation, the heating power can be calculated from the tank temperature variation as follows:

$$\dot{Q} = mc_p \dot{T}_t \qquad \textbf{Eq. 3}$$

where: m is the water mass contained in the tank, c_p is the specific heat capacity of the water and T_t is the tank water temperature.

In addition, the principal variable can be changed from time to the tank water temperature as follows:

$$COP_{int} = \frac{\int_{T_i}^{T_f} mc_p dT_t}{\int_{T_i}^{T_f} \frac{mc_p dT_t}{COP_{ins}\left(T_t\right)}} \approx \frac{\int_{T_i}^{T_f} dT_t}{\int_{T_i}^{T_f} \frac{dT_t}{COP_{ins}\left(T_t\right)}} \qquad \textbf{Eq. 4}$$

because m and c_p are practically constant, which allows the expression of COP_{int} to be simplified. Eq. 4 allows the COP_{int} to be calculated if the variation of COP_{ins} as a function of T_t is known. The next section presents some correlation-based models of COP_{ins} as a function of T_t, drawn from the scientific literature.

Existing correlation models

According to (Morrison, Anderson, & Behnia, 2004), for an air cooled HPWH, the instantaneous performance can be expressed by:

$$COP_{ins} = \left[a_1 + a_2\left(T_t - T_d\right)\right]\left[1 - a_3 \frac{T_d - T_w}{T_d - T_{dew}}\right] \qquad \textbf{Eq. 5}$$

where a_1, a_2, a_3 are constants; and the subscripts *d*, *w* and *dew* refer to dry bulb, wet bulb and dew point of the surrounding air temperature, respectively, and T_t is the tank water temperature.

This correlation model was validated using experimental data from two HPWHs: one with a wrap-around condenser coil and the other with an external condenser. The tests were carried out under different ambient conditions without a draw-off cycle. Compared to the measured values, the correlation model gave an average error of 4 % with a maximum error of about 15 % (Figure 18).

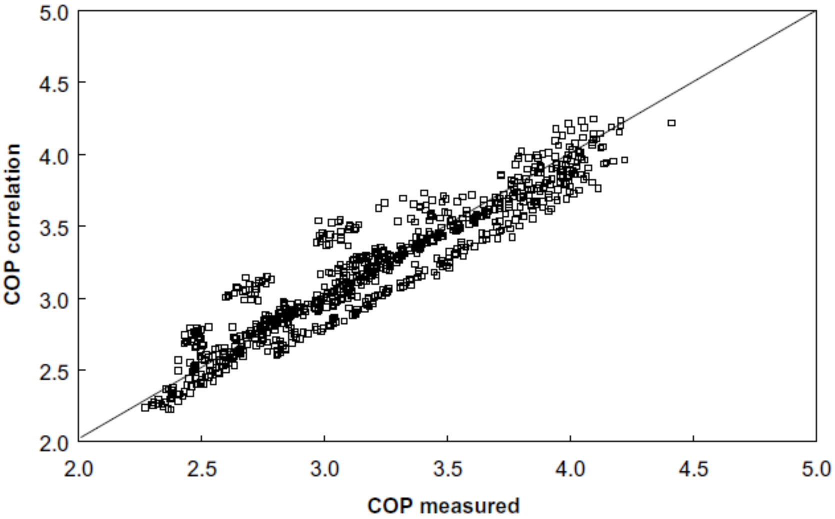


Figure 18. Comparison of measured COP and the corresponding value from the correlation model (Morrison, Anderson, & Behnia, 2004)

During the development of the standard (AS/NZS 5125.1, 2010), a number of alternative correlation functions, including the model presented above, were investigated from which the following model was selected:

$$COP_{ins} = c_0 + c_1\left(T_t - T_d\right) + c_2\left(T_t - T_d\right)^2 + c_3\left(T_w - T_{dew}\right) \qquad \textbf{Eq. 6}$$

In another analysis of an air-cooled HPWH, known as the EnergyPlus simulation (EnergyPlus, 2012), the following correlation is proposed:

$$COP_{ins} = c_1 + c_2 T_a + c_3 T_a^2 + c_4 T_t + c_5 T_t^2 + c_6 T_a T_t \qquad \textbf{Eq. 7}$$

where the c coefficients are constants; and T_a is either the dry bulb temperature or the wet bulb temperature of the ambient air.

Derivation of correlation models to be tested in the current study

In both of the correlation models presented above the water tank temperature is used. However, there are differences in the parameterisation of the models on the air side of the HPHW. While the EnergyPlus model (Eq. 7) uses a single air temperature (either dry bulb temperature T_d or wet bulb temperature T_w), Morrison's model (Eq. 5) and the AS/NZS standard model (Eq. 6) require three temperatures: T_d, T_w and the dew point temperature T_{dew}.

In the current study, the accuracy of the AS/NZS model, which contains 4 variables, is tested against the HPWH data gathered by KTL. It's worth noting that the air temperatures (T_d, T_w and T_{dew}) are generally correlated in the test standards. For example, the correlation coefficient of T_d and T_w is 0.97 from the four HPWH tests conducted under the AS/NZS standard conditions carried out by KTL. Therefore including all 3 air temperatures in the correlation model presents a degree of a redundancy and is therefore probably inappropriate. For this reason, a three-variable model based on T_d and T_w and a two-variable model using only T_w are also considered. In summary, the current study investigates the following correlation models[25]:

---

[25] The 2-variable model is in fact the EnergyPlus model reduced to one degree

4-variable model

$$COP_{ins} = c_0 + c_1 \left(T_t - T_d\right) + c_2 \left(T_t - T_d\right)^2 + c_3 \left(T_w - T_{dew}\right)$$

Eq. 8

3-variable model

$$COP_{ins} = a_0 + a_1 T_d + a_2 T_w + a_3 T_t$$

Eq. 9

2-variable model

$$COP_{ins} = b_0 + b_1 T_w + b_2 T_t$$

Eq. 10

The coefficients can be determined by regression using physical test data. While the air temperatures are obtained from measurements made of the ambient air, the most appropriate data used to define the water temperature T_t varies with the HP system technology. In general, T_t should be the average water temperature in the condenser. In the case of separate HPWHs that have a circulation pump between the tank and the HP, T_t is a function of the temperature at the inlet and outlet of the condenser. For integral condenser HPWHs, the definition of the tank water temperature should be based on the average water temperature over the depth of the condenser coil positioned in the tank or wrapped around the tank.

However, in this T_t is considered to be the tank water temperature averaged over the whole depth of the tank. This is done out of necessity due to the lack of information in the KTL HPWH experimental test data set provided for the analysis of these models regarding the water temperature at the condenser[26] and the limited information about the HP system configuration. In principle this could introduce significant error if the temperature at the condenser inlet differs from the water tank temperature (for separate tank-HP systems) or if the tank is stratified (for integral condenser HPs).

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[26] The water temperature at the condenser outlet was not recorded. The inlet tank temperature is not available either, except for the case of the KS tests.

C3. Methodology

This section illustrates how a HPWH energy performance model can be developed and investigates the precision of the models derived. Figure 19 summarises the main modelling steps, which are subsequently explained in the text.

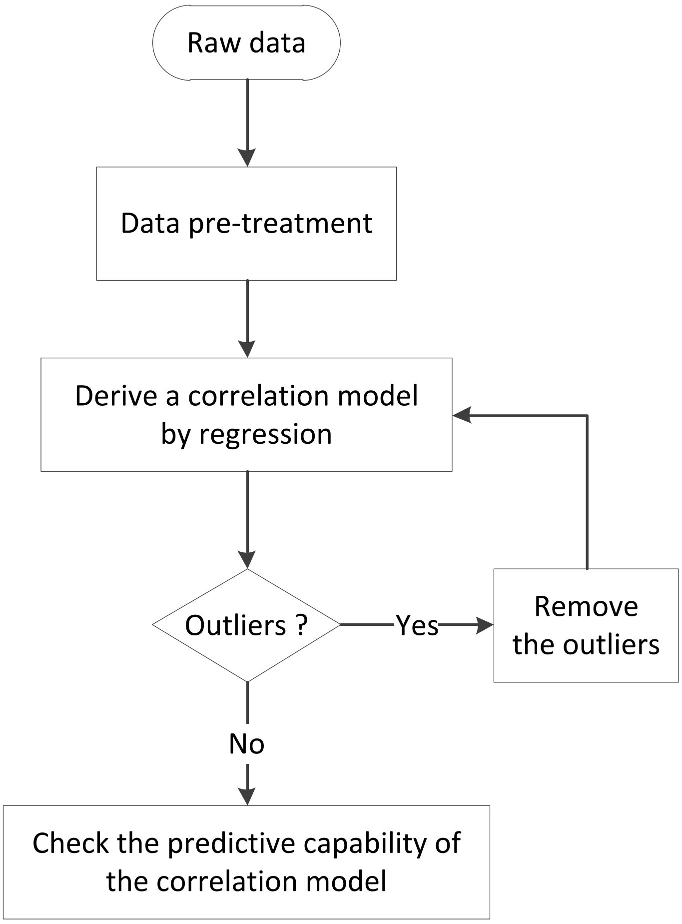


Figure 19. Methodology for modelling HPWH energy performance

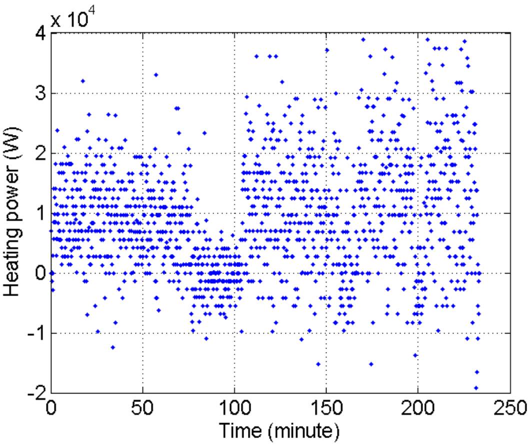
Data pre-treatment

First, the raw data needs to be pre-treated. Figure 20a shows the heating power calculated directly from the raw data (recorded at a 10 second interval) in the 4 AS/NZS tests of HPWH Model B, from which a high level of statistical noise is observed. Given this, it is better to average the measured data over an appropriate period of time during which the water temperature variation is significant, especially when compared to the measurement uncertainty. In this report, two levels of temperature variation are studied: 1K and 5K. In the case of HPWH Model B, because the water temperature is mostly linear with time, these two levels of variation can be obtained by taking averages over periods of 1 minute and of 5 minutes, respectively (see Figure 20b and Figure 20c)[27].

---

[27] For all three of the HPHWs tested (Models A, B and C), the water temperature rises gradually over time; however, there are some HP systems that exhibit a significant reduction of heating capacity at higher water temperatures. Such systems have longer operating times at higher water temperatures than at lower water temperatures. Thus, the period of time required to take an average should vary with the

(a) Δt=10 seconds



(b) Δt=1 minute

(c) Δt=5 minute

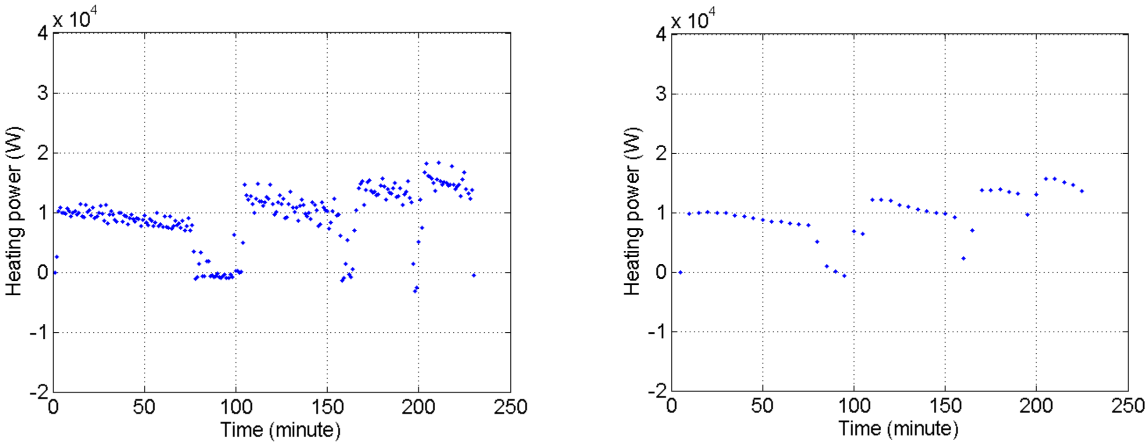


Figure 20. Heating power measured at 10 second intervals (raw data) and averaged over 1 and 5 minute intervals

Correlation model determination

The least squares method is used to determine the parameters of the three correlation models presented in Eq. 8, Eq. 9 and Eq. 10. The method of least squares is a standard approach to develop a regression model. It aims to minimise the sum of the squares of the errors between the model and the experimental data.

Outliers

An outlier is defined as an observation that is separated in a particular way from the rest of the data set. In a heating-up phase test, there are generally outliers at the beginning and at the end of the heating phase.

The outliers should be removed from the data because they can significantly affect the parameters derived for the correlation model. One effective way to find outliers is via

---

water temperature so that the change in water temperature remains constant to either 1 K or 5 K. Otherwise, the resulting COP regression model would be biased at high temperatures.

residual analysis. In this analysis, a criterion of a “studentised residual” of greater than 3 is used to define an outlier[28].

Once the outliers have been excluded, a regression model can then be refitted to the data. It is for this reason that an iterative loop is required to repeat the regression until there are no outliers left. In general the outliers are most commonly located at the start or at the end of the test (Figure 21).

Validation of the correlation model

In order to test the validity of the correlation model experimental test data is used to check the predictive capability of the correlation model obtained. Specifically, the estimated COP_{ins} derived from the correlation model is compared to the measured values and the magnitude of error determined. It is worth noting that the test data applied in this validation exercise must not have been used to define the model during the regression step i.e. that the data used to validate the model must be independent of that used to derive it. Finally, the COP_{int} over the entire test is determined using Eq. 4. The predictive capability of the model is quantified via the error of the model, which is defined as:

$$\varepsilon = \frac{COP_{int}}{COP_{int}^{measured}} - 1 \qquad \textbf{Eq. 11}$$

C4. Performance models based on AS/NZS test data

Among existing international performance test standards, the AS/NZS standard (AS/NZS 5125.1, 2010) is the standard that requires the greatest number of different test conditions during the heat-up phase. So, in principle a correlation model fitted to the AS/NZS test data could help in predicting heat-up phase performance of other international test standards. Prior to doing this, however, the methodology proposed for the AS/NZS tests was tested. For this purpose, data from three of the AS/NZS tests are used to develop a regression model and data from the 4th test is used to verify the model obtained. The test conditions are presented in Table 15. This result in four scenarios in total: as shown in Table 10.The simulation results derived for HPWH Model B are presented in the remainder of this section.

	Tests conditions as defined in AS/NZS 5125 model determination	**Test used for the model validation**
Scenario 1	2, 3 and 4	1
Scenario 2	1, 3 and 4	2
Scenario 3	1, 2 and 4	3
Scenario 4	1, 2 and 3	4

Table 10. Different scenarios used to model and check heat-up phase performance using AS/NZS test data

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[28] A studentised residual represents the ratio of the error of an observation compared to the estimated value and the standard deviation of the entire data. It is standard practice, for a studentised residual value of 3 or more to indicate a potential outlier.

As an example, Figure 21 shows a regression model of three variables developed from the data of tests numbered 1, 2 and 4. The heat-up model gives satisfactory regression R^2 coefficients of above 85% in all cases.

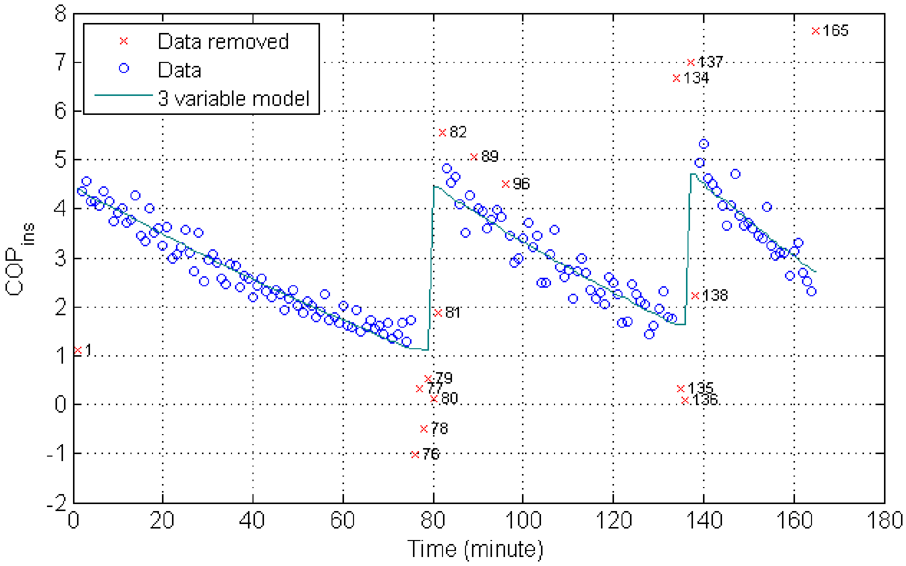

Figure 21.COP$_{ins}$ correlation models derived from the data of tests n° 1, 2 and 4

The next section presents the results derived from the data averaged over 1 minute and 5 minute time intervals.

C5. Correlation models derived from 1-minute interval data

Figure 22 shows the correlation models from the four different scenarios, compared to the measured data, where the correlation models are built from 1-minute interval data. For all the scenarios, the COP_{ins} values predicted by the models are relatively close to the measured values. Table 11 gives the details of the regression models obtained, with the coefficients of determination R^2 and the errors ε associated with each model (calculated via Eq. 11). The R^2 are relatively high, ranging from 85% to 93% which indicates a good fit between the modelled and measured data.

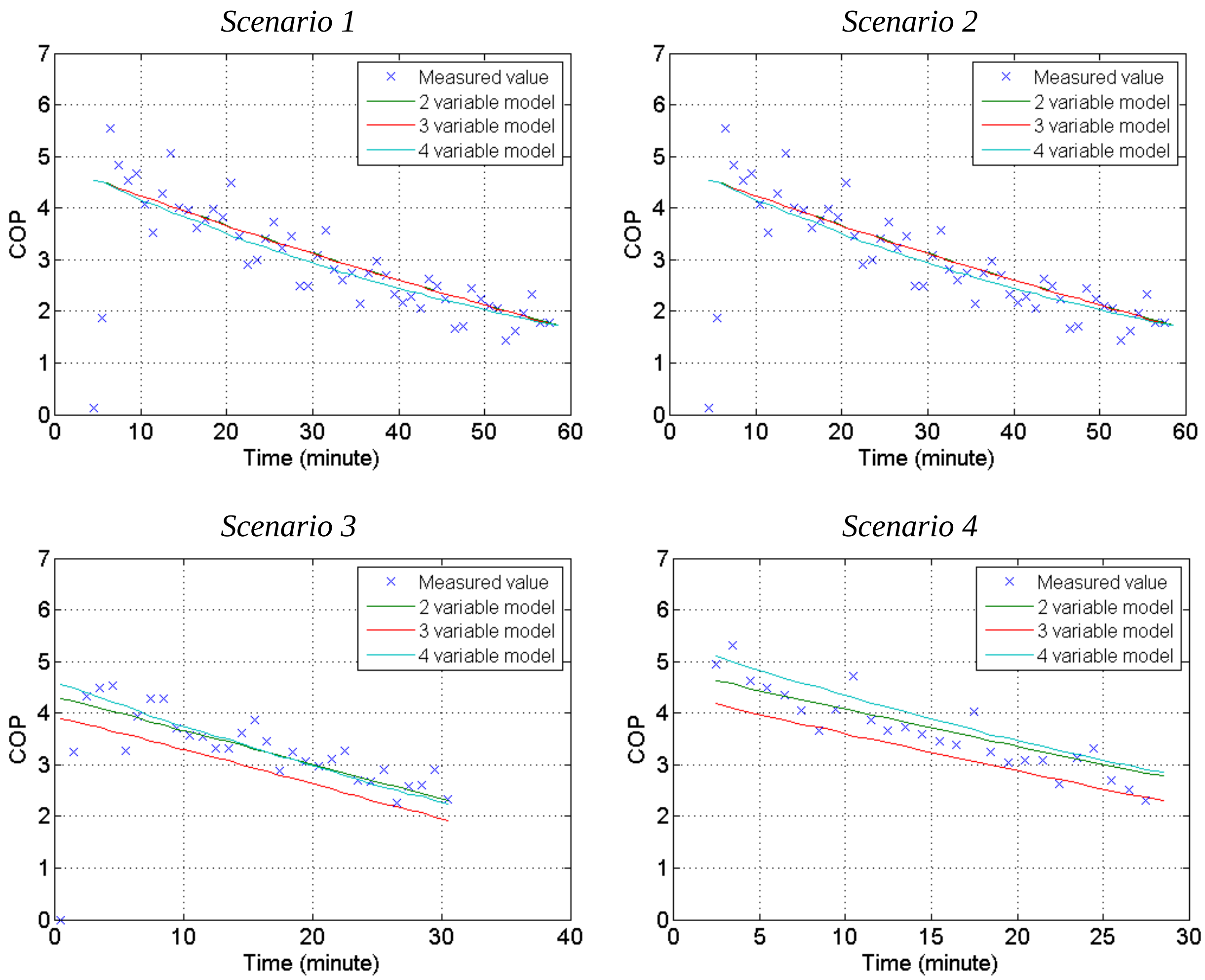

Figure 22.COP$_{ins}$ predictive capability of the correlation models derived from 1-minute interval data, for the different model derivation/validation scenarios

The errors ε are also exhibited graphically in Figure 23. This illustrates that all the models have a satisfactory precision, especially in the case of the model of two variables in scenario 4. The two-variable and four-variable models generally produce lower errors than the three-variable models. In the case of the two-variable models, Scenario 1 leads to a greater bias while the greatest bias occurs for Scenario 4 in the case of the four-variable models. Both cases involve the extrapolation of the COP value at outdoor temperatures which are outside the range of the data available to establish the model. (Note that the loss of accuracy that could arise from this would be even greater were the same model to be used for other international test standards, as the outdoor temperature can be even lower than 10 °C, which is the minimum outdoor temperature specified in the AS/NZS standard). Scenarios 2 and 3, which are derived from interpolation, give better results.

It should be added that, compared to the two-variable model, the three- and four-variable models may be penalized because of the correlation between the wet bulb temperature and the dry bulb temperature in the AS/NZS standard (see Appendix C). In real life, humidity and temperature are not generally correlated and the three and four variable models may be more accurate than the two variable model.

Scenario	Model	R^2 (%)	Error ε (%)
2 variables			
1	$COP = 4.8 + 0.069T_w - 0.076T_t$	85	-7.1
2	$COP = 4.4 + 0.067T_w - 0.066T_t$	92	+3.3
3	$COP = 4.5 + 0.064T_w - 0.067T_t$	84	-3.0
4	$COP = 4.4 + 0.068T_w - 0.066T_t$	91	<-0.1
3 variables			
1	$COP = 4.8 + 0.014T_d + 0.051T_w - 0.076T_t$	85	-8.8
2	$COP = 4.5 + 0.016T_d + 0.045T_w - 0.067T_t$	93	+3.0
3	$COP = 4.4 - 0.055T_d + 0.13T_w - 0.067T_t$	85	-15.0
4	$COP = 4.7 + 0.053T_d - 0.023T_w - 0.066T_t$	91	-13.3
4 variables			
1	$COP_{ins} = 4.3 - 0.083\left(T_t - T_d\right) + 4.9*10^{-4}\left(T_t - T_d\right)^2 - 0.13\left(T_w - T_{dew}\right)$	83	-2.2
2	$COP_{ins} = 4.3 - 0.080\left(T_t - T_d\right) + 4.2*10^{-4}\left(T_t - T_d\right)^2 - 0.14\left(T_w - T_{dew}\right)$	93	-1.6
3	$COP_{ins} = 4.4 - 0.082\left(T_t - T_d\right) + 4.4*10^{-4}\left(T_t - T_d\right)^2 - 0.18\left(T_w - T_{dew}\right)$	91	-3.8
4	$COP_{ins} = 4.5 - 0.085\left(T_t - T_d\right) + 4.5*10^{-4}\left(T_t - T_d\right)^2 - 0.17\left(T_w - T_{dew}\right)$	92	+5.3

Table 11. Correlation models derived from 1-minute interval data

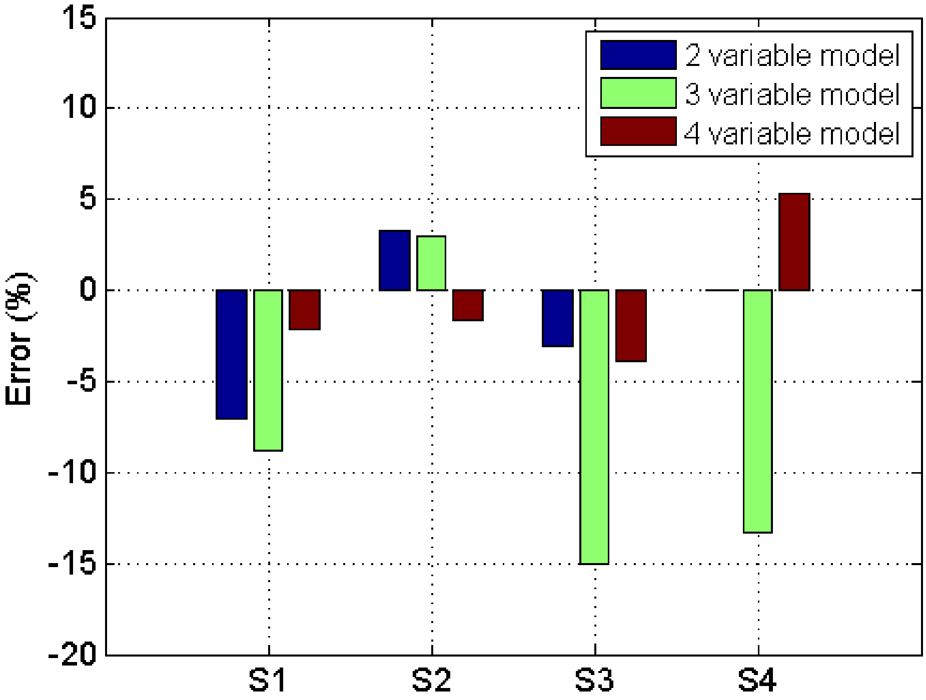

Figure 23. Error in COP_{int} predicted by the models derived from averaging over a 1-minute time interval compared to experimental measurements

Correlation models derived from 5-minute interval data

Figure 24 shows the correlation models from the four different scenarios, compared to the measured data, where the correlation models are built from 5-minute interval data. Figure 25 shows the associated errors ε as defined in Eq. 11, and shows that, while the two variable models always give satisfactory precision, the three or four variable models can have significant errors of up to 16 %.

In general, the models derived from 1-minute interval data give better predictions than the models based on 5-minute interval data. This probably results from the loss of information because of the longer averaging period. In addition, the data quality is significantly reduced, especially in test n° 4 where only four points (Figure 24) were available to fit the regression. Thus it can be concluded models based on data averaged over five minute time intervals are unlikely to result in an accurate regression model.

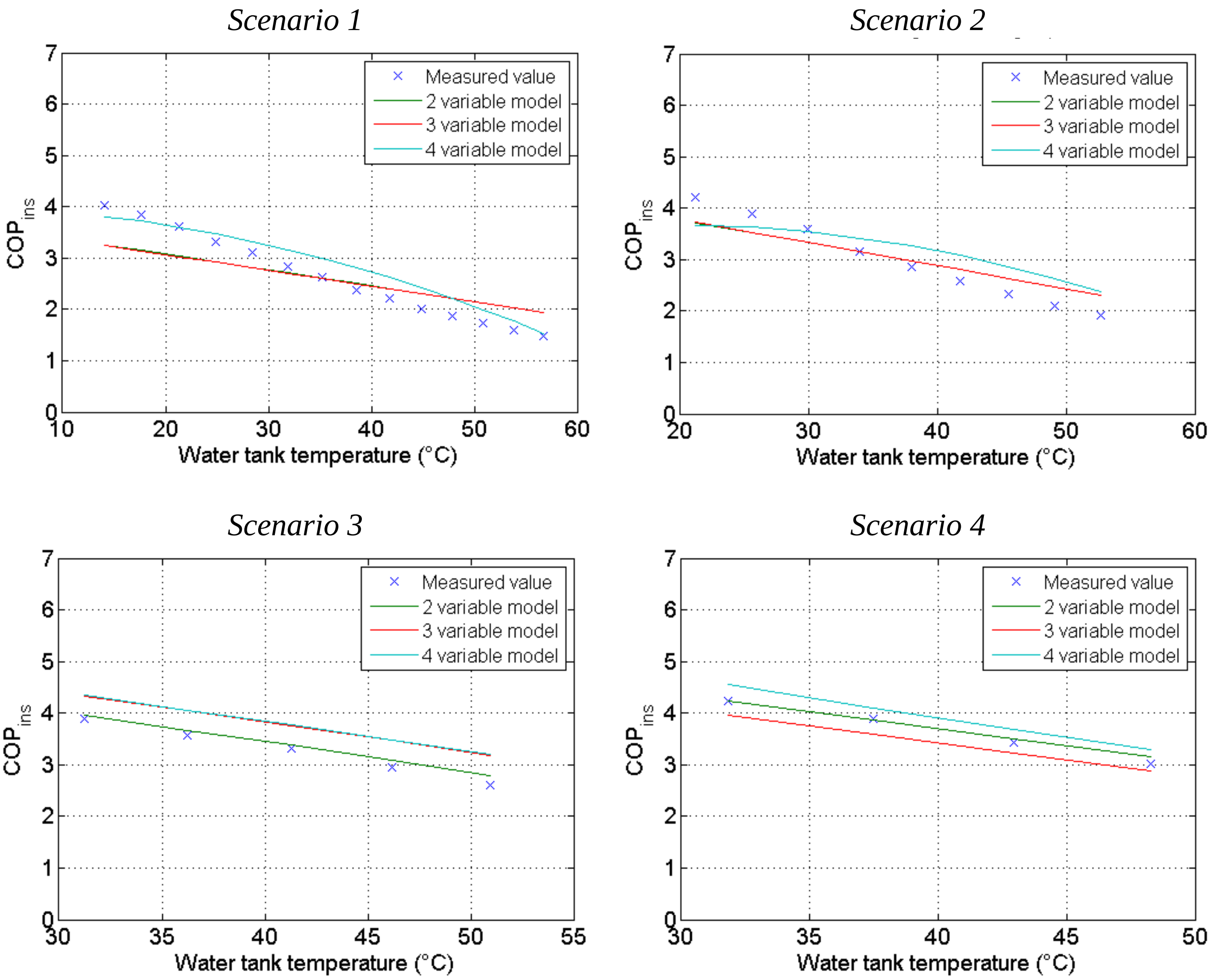

Figure 24.COP$_{ins}$ predictive capability of the correlation models derived from 5-minute interval data, for the different model derivation/validation scenarios

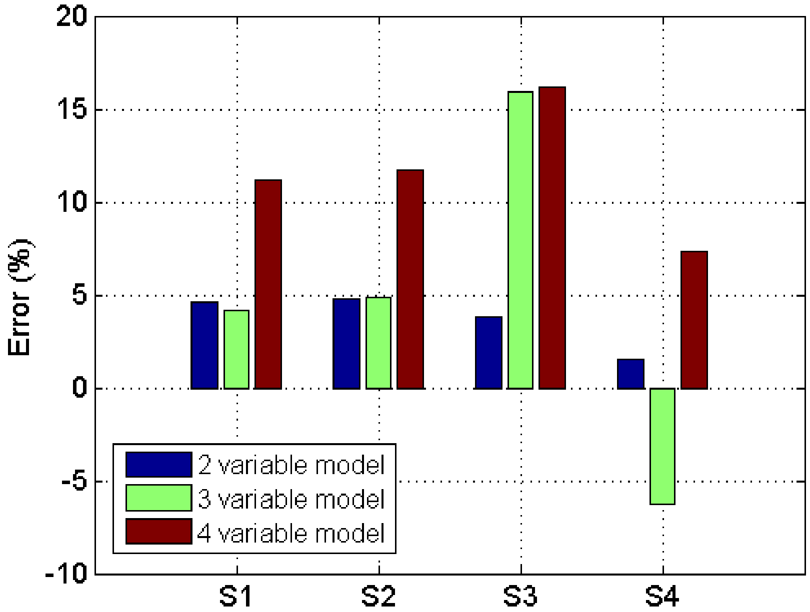

Figure 25. Error in *COP_{int}* predicted using the correlation models derived from 5-minute interval data compared to experimental measurements

Conclusion

This section presented modelling results derived from four sets of (AS/NZS 5125.1, 2010) tests for HPWH Model B. Experimental data from three tests is used to develop correlation models and the models obtained are compared to data from the 4th test (so, four scenarios are considered in total). Three types of model based on two, three and four variables were developed using the least squares regression technique. The models were built by averaging data over different time periods: one minute and five minutes, corresponding approximately to changes of 1 K and 5 K in the tank water temperature.

All the models obtained can have a reasonable precision in terms of their performance predictive capability. The models based on 1-minute averages and those based on 5-minute averages have the same level of precision, with the exception of the four-variable model, which has too many parameters to be accurately identified with the limited number of data points used for the regression and given the high correlation between the dew point temperature and the dry bulb temperature in the AS/NZS standard.

C6. Predictive capability of a model based on the heat-up phase and steady-state tests

This section aims to clarify how well a regression model derived from AS/NZS test data is able to predict the heat-up phase performance expected from standard test procedures used in other economies without carrying out physical tests. For this purpose, regression models are derived from a set of four (AS/NZS 5125.1, 2010) tests applied to HPWH Model B, according to the methodology proposed in section C3.
The predictive capability of the models obtained is then verified using test data for the same HPWH measured under the following standards: (U.S. Department of Energy), (EN 16147, 2011) and (JIS C 9220, 2011). The assessment only considers and applies to

the heat-up phase without draw-off.

The predictive capability of the correlation models derived from the AS/NZS tests are also compared to three sets of test data measured under the Korean Standard (Korean standard, 2013)[29]. These tests are performed under steady state conditions where the water is continuously drawn off with a constant water flow rate. Table 12 summarises the operational conditions applied in the different test standards.

	Outdoor (air)		**Indoor (water)**				
Test	Dry bulb (°C)	Wet bulb (°C)	Water in (°C)	Water out[30] (°C)	Flow rate (l/min)	Water tank T_t (°C)	Stratification degree[31] (°C)
USA	19.6	13.6	NA	NA	0	ranging 14 – 56	0.3
Europe	20	15	NA	NA	0	ranging 10 – 56	0.2
Japan	15.9	12.1	NA	NA	0	ranging 17 – 57	0.2
Korea T1	7.0	6.0	15.1	50	3.4	49.7	0.2
Korea T2	2.0	1.0	41.1	45	22.0	43.9	0.6
Korea T3	7.0	6.0	40.1	45	22.0	43.8	0.8

Table 12 Summary of test data for various test standards applied to HPWH Model B (NA = not available)

It is worth noting that the tank water temperature is required to simulate the HP performance under a specific standard, for which the following two cases can be distinguished:

- the tank water temperature is unspecified under the Korean standard and for this reason, the tank temperature is assumed to be equal to the water draw-off temperature, which is clearly specified in the standard[32].
- for the other standards the tank water temperature at the beginning of the heat-up phase is specified. In this case, the temperature at the end of the phase is an intrinsic characteristic of the HP and can be determined from the AS/NZS tests.

Figure 26 and Figure 27 exhibit graphically the error ε in the 1-minute interval data and 5-minute interval data models. In both cases, the models obtained have reasonable

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[29] It should be noted that while experimental data was made available for six sets of Korean standard tests only three of them are used in this comparison due to reliability issues with the test data. For the three data sets that were unused the reported wet bulb and dry bulb temperature values are identical, which implies the relative humidity is 100% which violates the specified test standard relative humidity requirements.

[30] The draw-off water temperature is not recorded during the physical tests. The values shown in the table are thus just those specified in the test standard requirements.

[31] The degree of stratification is defined as the standard deviation of the six different water temperature values measured along the height of the tank.

[32] In general, this hypothesis is always satisfied because the water temperature in the tank is relatively homogeneous (e.g. is not stratified) when there is a continuous draw-off flow. Analysis of the available experimental data also confirms this point as it shows a maximum difference of only 1 K between the average tank temperature and the water draw-off temperature (see Table 12).

precision for almost all the test standards, except for the Korean test n°1. The main difference between this test and the others relates to the very low inlet water temperature when compared to the water tank temperature. As discussed in section C3 this is because the correlation models are likely to be inaccurate when the tank water temperature differs greatly from the condenser water temperature.

The same assessment is also carried out for HPWH Model C (see Appendix B). The results also show the models have a good predictive capability except for the same Korean test n°1.

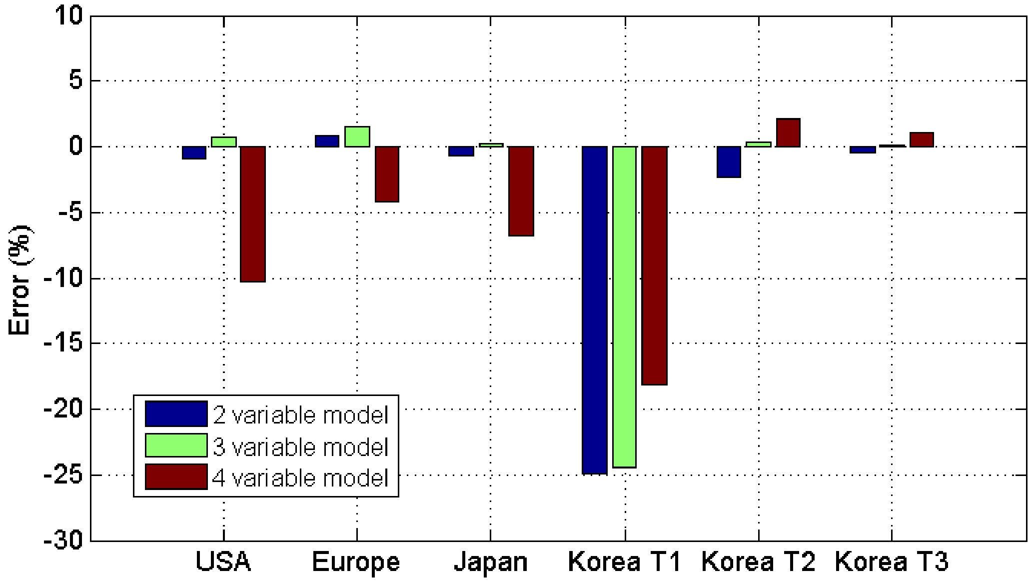

Figure 26. Error in COP_{int} predicted by the correlation models derived from 1-minute interval data compared to experimental measurements

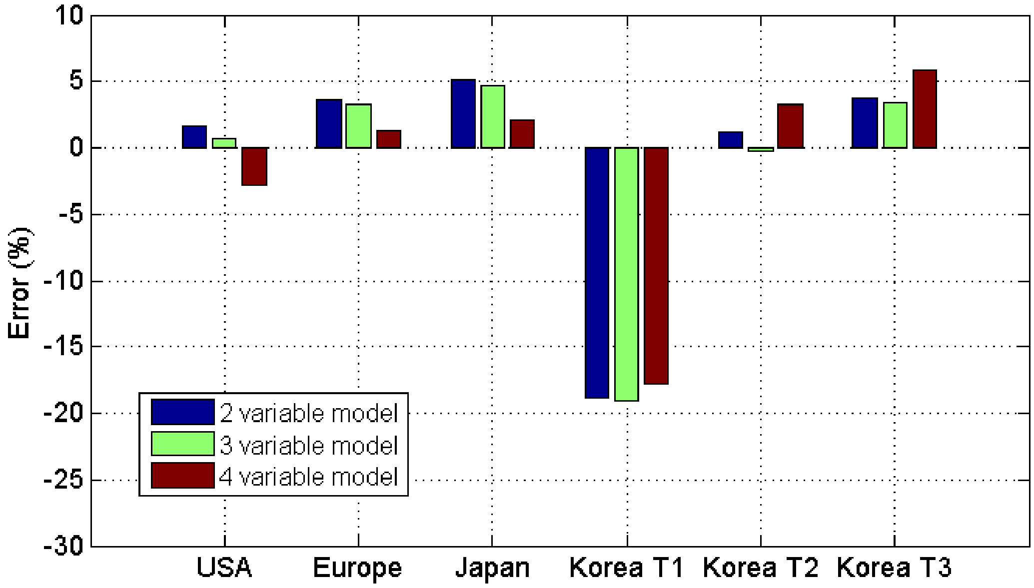

Figure 27. Error in COP_{int} predicted by the correlation models derived from 5-minute interval data compared to experimental measurements

In the case of HPWH Model B, the four-variable model produces relatively large errors for several tests, while for HPWH Model C the three-variable model gives poorer results compared to the other two models for almost all tests. This may lead to a conclusion that the two-variable model is the most appropriate model to be used. Yet the models are all derived from the AS/NZS tests where the air temperatures (dry bulb and wet bulb) are highly correlated (Appendix C). In this case models using both dry and dew point air temperatures may be less accurate as they use redundant data. However, in principle the situation could be reversed in the case of uncorrelated temperature data. In general then, the four-variable model, which is derived from thermodynamic concepts, may give better results.

C7. Predictive capability of a model applied over a full test cycle including draw-offs

Methodology for modelling performance over a full test

The HPWH performance simulation methodology proposed in the previous section was only applicable for the heat-up phases without the inclusion of draw-offs, or to steady state conditions when water is drawn-off at a constant continuous flow rate (as with the Korean test standard). This section investigates the feasibility of applying this steady state model to model a full test that includes a draw-off pattern. In order to do so, the following issues need to be addressed:

- Tank heat losses to the environment; while, tank heat losses can be neglected when compared to the heating capacity of the HPWH during a heat-up phase, they need to be accounted for over a longer time period. Indeed, draw-off tests may include long time periods where the HP is not heating and during which the heat losses represent a significant part of the energy balance.
- Modelling draw-off cycles requires a time simulation as changing the driving variables (from time variable in Eq. 2 to water temperature in Eq. 4) is not permitted because the tank temperature is no longer a monotonic function of time. Therefore, a COP model depending only on temperature variables is insufficient. The heat-pump’s heating capacity, and thereby the evolution of the tank water temperature over time, can be deduced from a supplementary model that gives electricity consumption as a function of temperature variables.
- A control-logic model is also required. It should indicate the start and stop times of the HP when operated under a given standard test cycle.

Figure 28 summarises the methodology put forward to model the HPWH operation over a full test cycle including draw-off periods. The following steps are required:

- First, regression models of COP and electric power are developed, using experimental test data measured under different operational conditions (for example the AS/NZS test cycle). It is also necessary to develop a heat loss model, from the analysis of a cooling-down period. In addition, a control logic model needs to be determined by observing the operation of the HP.
- Second, the initial variable values are set in accordance with the specifications of the test standard in question.

- The third step is to model the water temperature over time. For each time step, the water temperature is calculated by considering the heat losses, the draw off flow and the HP heating effect. Then, the operational mode of the HP (on or off) is determined.
- Finally, the simulation results are checked by comparison with the measured values.

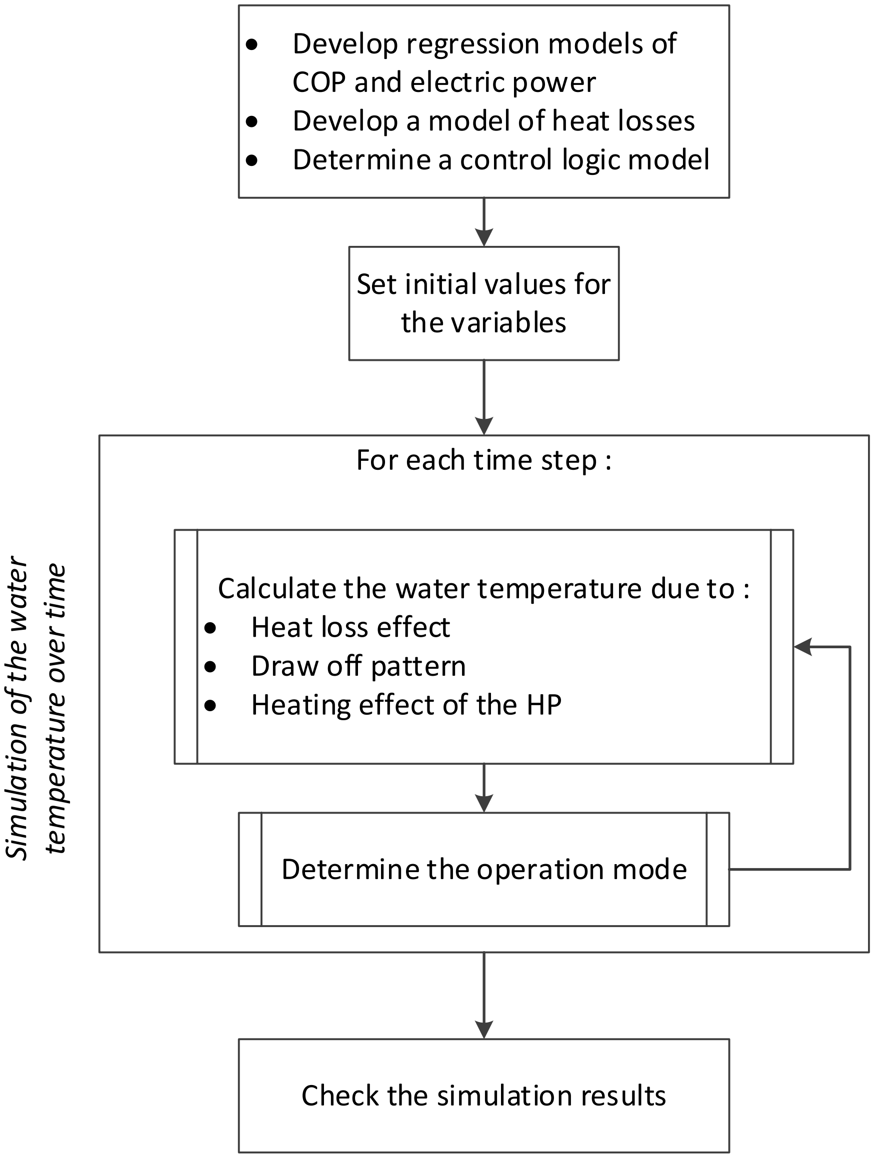

Figure 28. Methodology for modelling HPWH operation over a full test cycle

This methodology was applied to experimental data for the HPWH Model B to develop a model such that regression models are derived using four sets of AS/NZS tests. The heat loss model and control model are determined from the analysis of data taken from a test period where the HPWH is in stand-by operation. The performance of the HP was then simulated according to the US test conditions and the predicted results compared to the measured values[33].

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[33] Among all the experimental tests that include draw-offs only the US test was used for this analysis. In the case of the other tests, the draw-off flow rates and start / stop times are not recorded in the

Tank heat losses to the environment

Water tank heat losses can be modelled as follows:

$$\dot{Q}_{loss} = UA*(T_t - T_{amb}) \qquad \textbf{Eq. 12}$$

where T_{amb} is the temperature of the ambient air surrounding the tank and UA is the tank heat loss coefficient. As T_{amb} is specified in the test standards, the factor UA can be derived from a cooling period (i.e. where the HP is stopped and the water tank temperature decreases due to the heat losses); however, this approach was not used in this study due to the lack of appropriate test data. In fact, there is no available test data when the water cools down to near to the cold water inlet temperature rather the cooling periods available are for when the HP is in stand-by. In these conditions, the variation of T_t is too small (less than 3 K) to allow the UA factor to be accurately determined. For this reason, the following model is used in place of Eq. 12:

$$\Delta T_t = C_{loss} * \Delta t \qquad \textbf{Eq. 13}$$

Where ΔT_t is the variation of T_t over a period of time Δt, and the factor C_{loss} can be determined from available test data.

Data for four cooling phases were extracted at random from the US test cycle data and used to calculate C_{loss} as shown in Figure 29. All four phases show that C_{loss} = 0.031 K/min[34]. This value is then used in the subsequent full-test simulations. It should be noticed that the model based on Eq. 13doesn’t take into account the ambient temperature around the tank; consequently, the model is only appropriate if the tank water temperature has a small variation around the set point and the ambient temperature remains constant.

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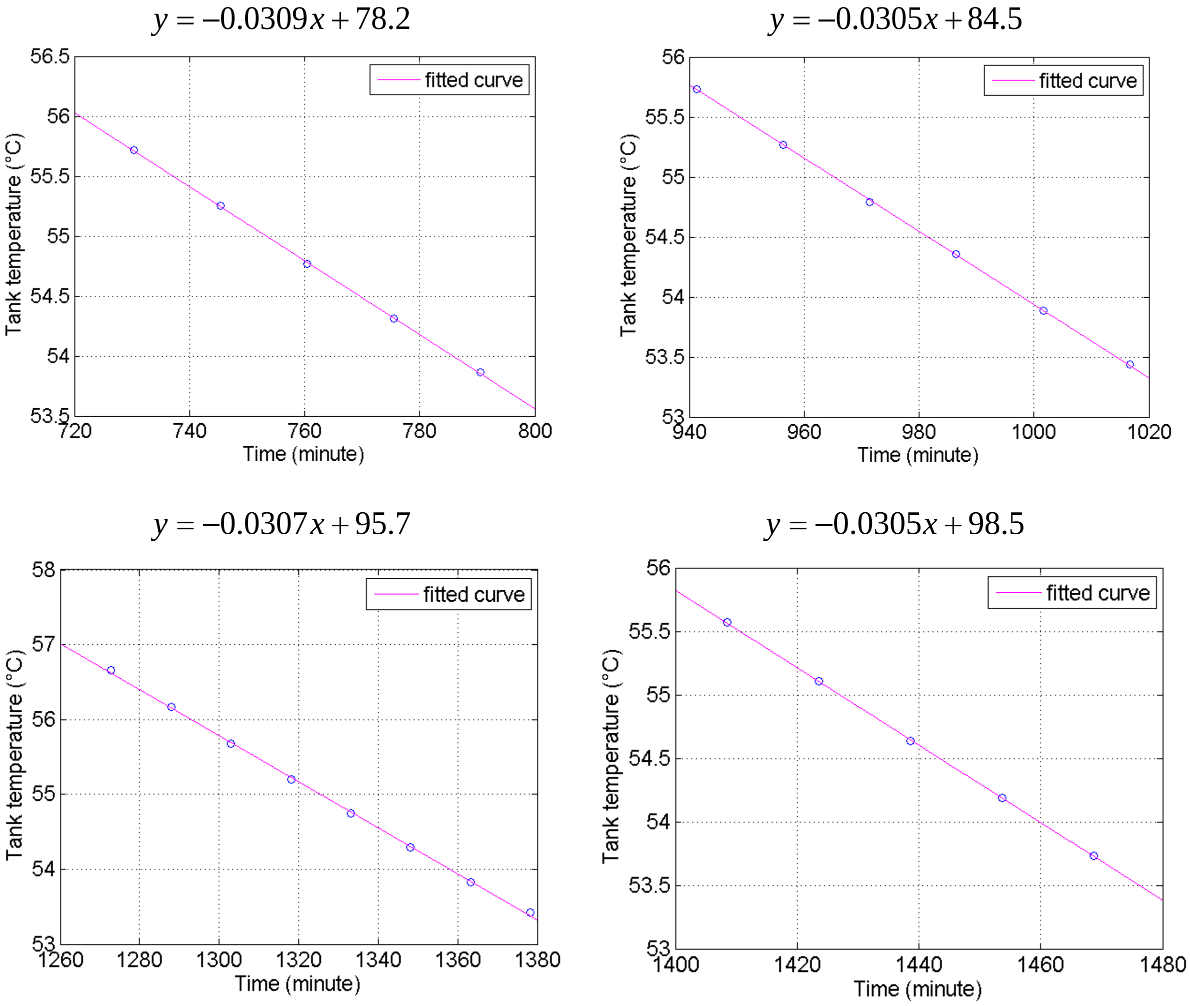
experimental data sets, and in most cases the sequences cannot be easily observed from the water temperature variation (due to the draw-off flow rate being too small compared to the tank volume and the fact that the tests were not done in full accordance with the test standard requirements). Only in the case of the US test was the evolution in the tank water-temperature clear enough for start/stop times of the draw-offs to be detectable with an acceptable level of accuracy.

[34] For an accurate determination of C_{loss}, data should be averaged over a relatively long period of time as the change in water temperature is very small. In this study, a period of 15 minutes is used.



$y = -0.0309x + 78.2$

$y = -0.0305x + 84.5$

$y = -0.0307x + 95.7$

$y = -0.0305x + 98.5$

Figure 29.Evolution of the tank water temperature over time for different cooling phases

Electric power modelling

As for the COP model development, three electric power models are investigated: a linear model of three variables based on the dry bulb and wet bulb air temperatures and the tank water temperature; a linear model of two variables based on the wet bulb air temperatures and the water temperature and finally the model proposed in the (AS/NZS 5125.1, 2010) standard.

AS/NZS model[35]	$\dot{W} = c_0 + c_1\, T_t + c_2\, T_t^2 + c_3\, T_d$	**Eq. 14**
3-variable model	$\dot{W} = a_0 + a_1 T_d + a_2 T_w + a_3 T_t$	**Eq. 15**
2-variable model	$\dot{W} = b_0 + b_1 T_w + b_2 T_t$	**Eq. 16**

---

[35] The model used in the (AS/NZS 5125.1, 2010) standard is based on 3 variables (water tank temperature, inlet water temperature and dry air temperature). Because the inlet water temperature is not available in the data provided, it is replaced by the water tank temperature in Eq. 14.

The coefficients were determined by regression using the four sets of AS/NZS experimental test data. The models obtained were then compared to the measured values over the heat-up phase of the US test (Figure 30). The results show that all the models have excellent predictive capability, with errors ranging from 2.2 % for both the linear models down to as lows as 0.9 % for the AS/NZS model. As it produced the best result the AS/NZS model was selected for the rest of the analysis.

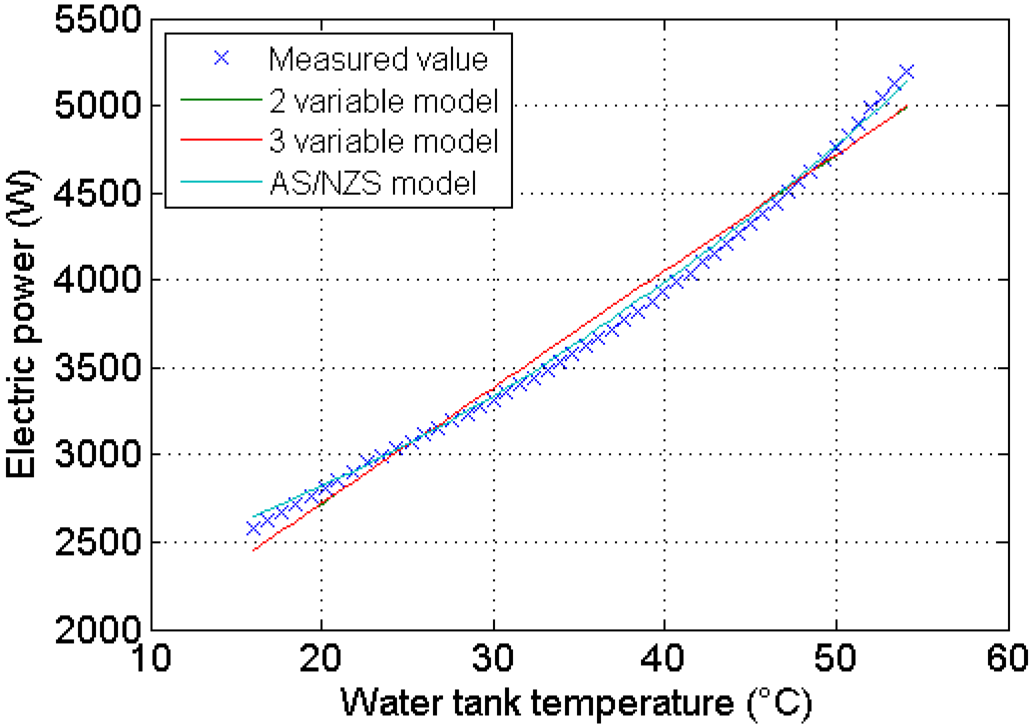


Figure 30. Electric power predictive capability of the correlation models

In principle the electric power drawn by the HP operating in stand-by mode should also be modelled to fully account for the total electric power demand over a complete test. Stand-by power is generally constant and easily measured thanks to a stand-by period in the test cycle. According to the KTL test data the stand-by power demand of HPWH Model B is zero.

Tank temperature model during a draw off cycle

During a draw-off period, the water tank temperature is considered to be homogeneous in the whole tank. This temperature is the equilibrium of the inlet water supply at a temperature T_{supply} and the water already in the tank at temperature T_t. Thus, the variation of the tank water temperature over a period of time Δt may be calculated as follows:

$$\Delta T_t = \frac{q\Delta t}{V}\left(T_t - T_{\text{supply}}\right) \qquad \textbf{Eq. 17}$$

where q is the water flow rate and V is the volume of the tank.

Control logic

A model of the control logic is necessary to simulate the evolution of the tank water temperature over time when a draw-off occurs or when the system is under stand-by operation. The control logic indicates the stop / start times of the HPWH. Observations of a period of stand-by operation (shown in Figure 31)indicate that the start/stop of the specific HP is controlled so that the water temperature remains within a narrow temperature band around 55 °C. The control logic is likely to be as follows:

- During a heating phase (when the HP operates) the water temperature increases to an upper set-point temperature T_{up} at which the HP stops.
- During a cooling phase (when the HP is in stand-by mode) the water temperature decreases until it reaches a lower set-point level T_{down} at which point the HP restarts.

For the HPWH Model B, it is estimated that T_{up} = 56.3°C and T_{down} = 53.3°C.

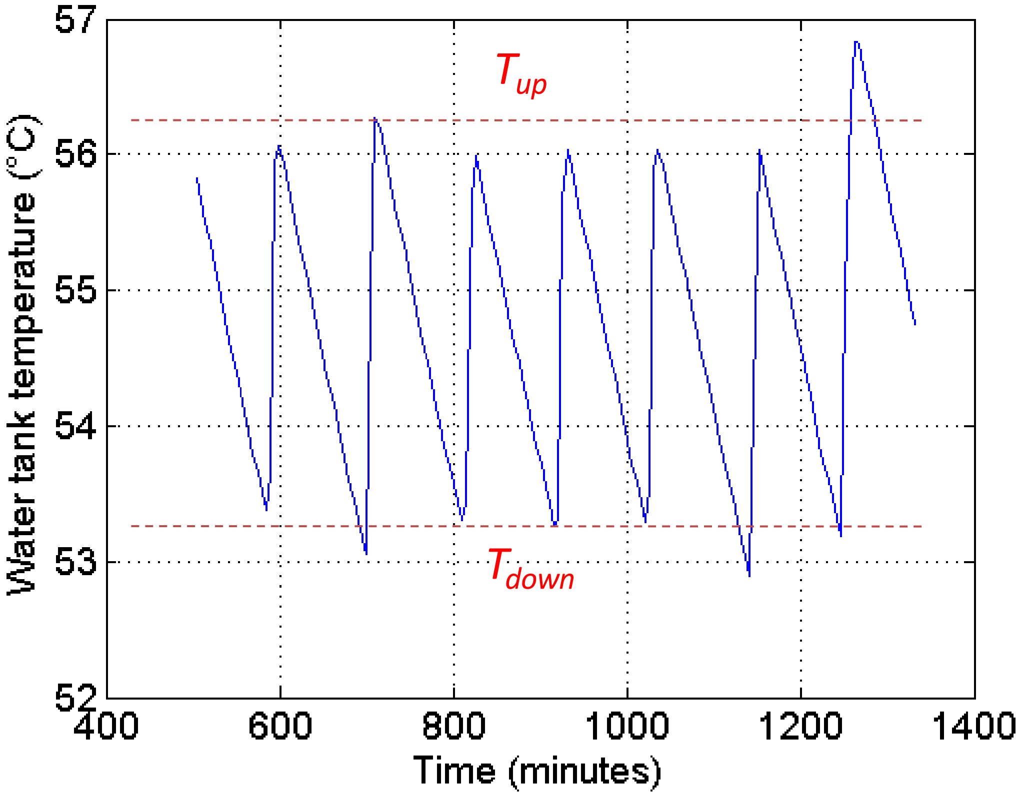


Figure 31. Evolution of the tank water temperature over time during a stand-by period (HPWH Model B)

C8. Simulation results

Figure 32 shows the evolution of the water tank temperature for both simulated values and experimentally measured values. The simulation values are generally close to the measured values, especially in the heat-up phase. A delay is observed in the simulated stand-by phases (with or without draw-offs)due to inaccuracy in the control model.

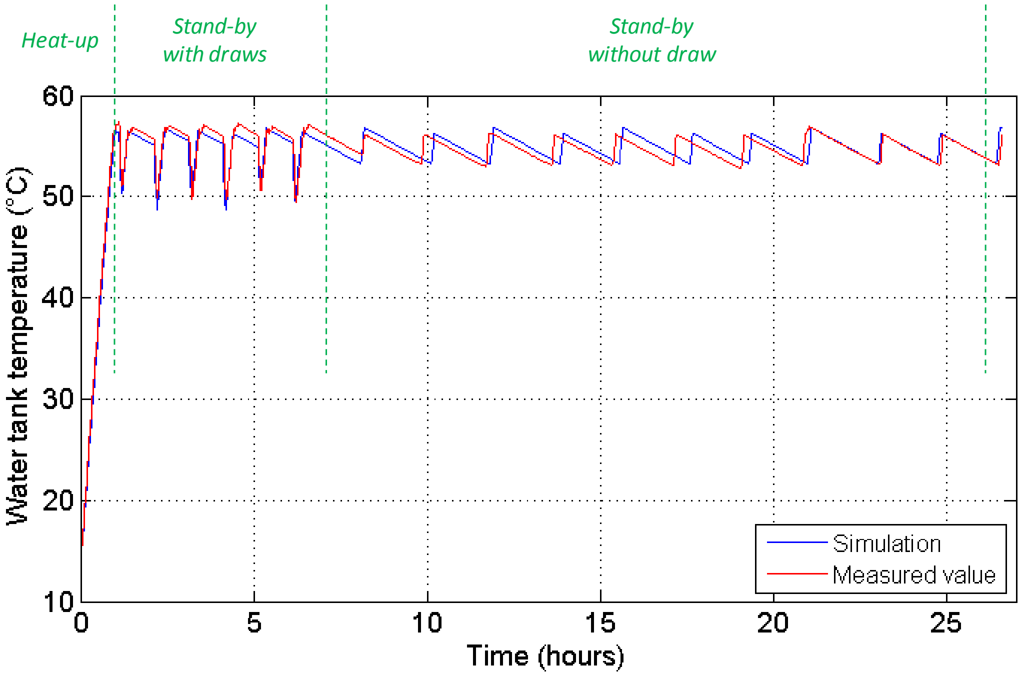


Figure 32. Predictive capability of the full test cycle model developed under the US test standard conditions

Table 13 compares the simulation results with the measured values. From this it is seen that the heating up time is predicted precisely, with an error as low as 0.6%. The COP error during the heat up phase is small, at about -1 %. The temperature loss, defined as the decrease of the tank water temperature due to the heat loss effect and/or the draw-off pattern, has an error of 1.2 % over the “stand-by and without draw” period. This indicates that the heat loss model functions correctly. The error over the “stand-by with draw” period is higher (+7.5 %), probably due to the estimated draw flow-rate used in the simulation[36]. The COP error in this phase is relatively high (-8.2%), resulting in an error of -6.7% for the whole test.

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[36] In fact, as the flow rate is not recorded, it is estimated from the variation of the water temperature over the draw off periods. For this purpose, Eq. 17 is used, where ΔT_t is measured, allowing the flow rate q to be determined.

		Simulated	*Measured*	*Error (%)*
Heat up phase				
Electric consumption	MJ	13.5	13.0	3.8
Heating up power	MJ	36.6	35.6	2.7
COP	-	2.7	2.7	-1.0
Heating up time	min	58.1	57.8	0.6
“With draw stand-by” phase				
Electric consumption	MJ	26.5	25.5	3.7
Energy of the drawn water	MJ	38.0	40.0	-4.8
COP	-	1.4	1.6	-8.2
Temperature loss	K	43.4	47.0	-7.5
“Without draw stand-by” phase				
Electric consumption	MJ	16.9	15.2	11.3
Temperature loss	K	31.9	31.6	1.2
Whole test				
Electric consumption	MJ	56.8	53.7	5.9
Heating energy	MJ	74.7	75.6	-1.3
COP	-	1.3	1.4	-6.7

Table 13.Comparison of the model simulation results and the measured values for different operational phases

C9. Limitations of the proposed methodology

Treatment of back-up electric resistance heaters

The results presented above show that it is possible to correctly model a HPWH that only uses a heat pump i.e. that does not also use a back-up electric resistance heater. This section aims to evaluate the feasibility of modelling a heat pump system that includes a back-up electric resistance heater. The experimental test data from the HPWH Model A is analysed for this purpose.

The following three operational modes are considered:

- periods when only the heat pump is activated
- periods when only the electric resistance heater is activated
- periods when both the heat pump and electric resistance are used

In principle it is necessary to develop a performance correlation model for each of these operational modes. A supplementary model of the control system is also required to be able to predict when each of these modes is operational. This model needs to determine the operational mode as a function of the operating conditions i.e. the air and water temperatures.

The control logic of the HPWH Model A is as follows:

- at the beginning of the test period both the HP system and electric resistance heater are used

- when the water tank temperature reaches a specified limit the resistance heater is turned down/off and only the HP works.

Figure 33 shows the water temperature operational-mode limit (i.e. threshold at which the HPWH operates in either the HP-only mode or HP and resistance heater mode) as a function of the dry bulb air temperature, observed from four sets of experimental tests under the AS/NZS standard. From these, the following linear-correlation function (with a coefficient of determination R^2=0.99) is derived for the threshold tank water temperature T_{lim} as a function of the dry bulb air temperature T_d:

$$T_{lim} = 0.47 * T_d + 14 \qquad \textbf{Eq. 18}$$

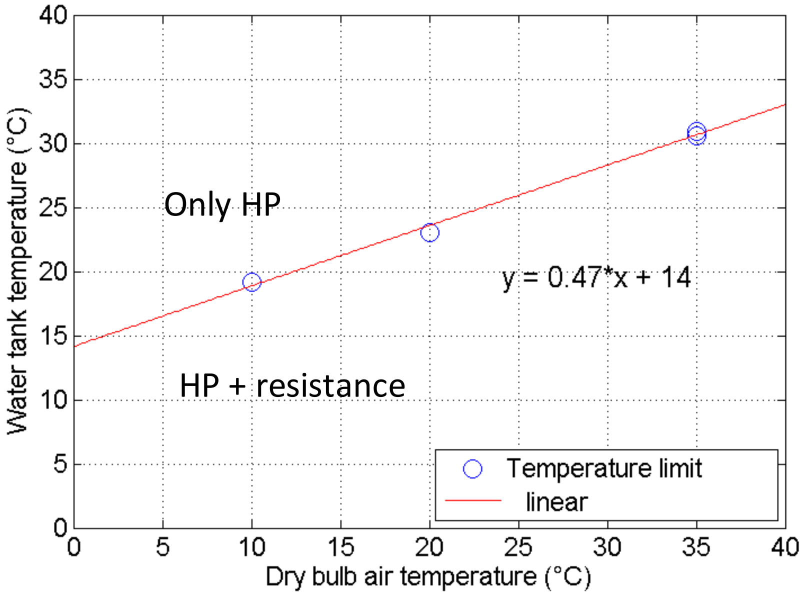

Figure 33. Temperature limit (thresholds) separating the two operational modes of the HPWH Model A, as observed from four sets of AS/NZS experimental test data

The AS/ZNS test data are also used to develop COP performance correlation models for each operational mode. Three types of models are derived and tested, using two, three and four-variables. The models obtained are then used to estimate the heat-up phase COP (i.e. without draw off) that would be expected under the Japanese standard test and the estimates are compared to the corresponding test data (Figure 34). It appears that the control model (Eq. 18) is not completely satisfactory for the Japanese test standard. Indeed, it underestimates the operational mode temperature limit by about 2 K. This error is probably due to the following factors:

- the control logic is not exactly determined from the tank water temperature, but from temperature sensors which are imperfectly correlated with the tank water temperature e.g. the condenser water temperature, or the refrigerant temperature
- the control logic may be more complicated than a simple linear model of air and water temperatures.

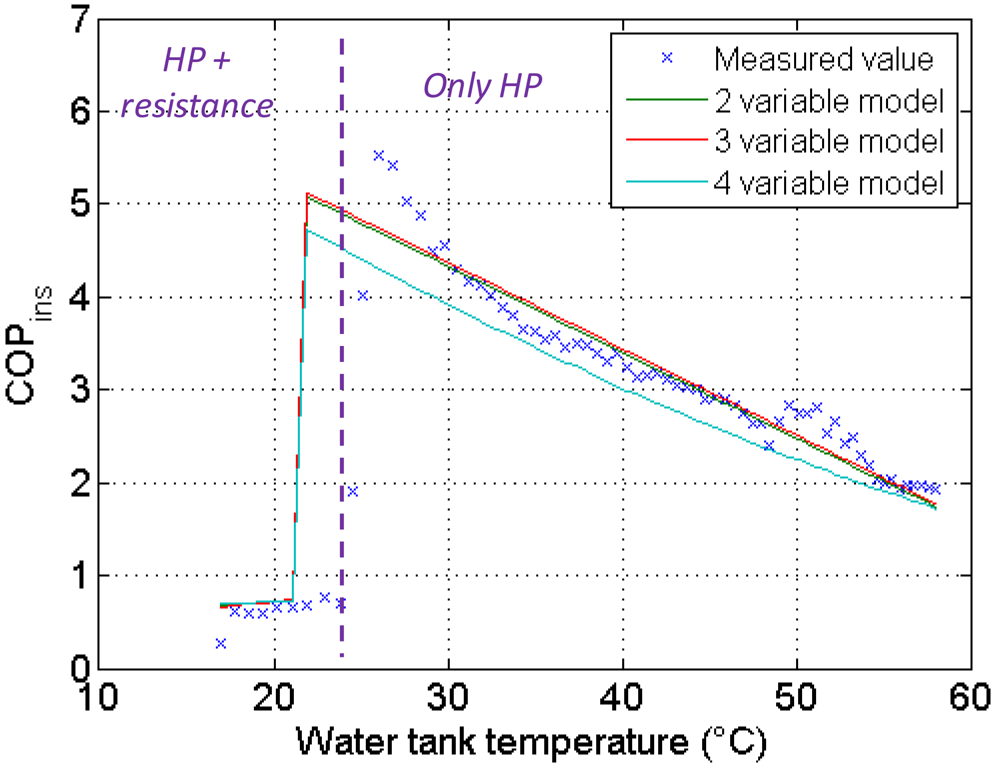

Figure 34. Predictive capability of the correlation models of the HP-electric resistance system (HPWH Model A)

Unfortunately, the relatively small error in the control correlation model leads to a significant overestimation of the predicted COP compared to the measured COP, with the error ranging from +15 to +22 % depending on the model type (Table 14).

Mode of operation	Electricity consumption (MJ)	Heating capacity (MJ)	Error of the COP predicted (%)		
			Model of 2 variables	Model of 3 variables	Model of 4 variables
HP+resistance	1.53	0.99	49.7	50.2	51.0
only HP	1.52	4.52	0.0	1.3	-8.6
total	3.05	5.51	21.2	22.4	15.1

Table 14. Division of the heat-up phase of the Japanese standard test

The observed error is explicable due to the following considerations:

- the HP+resistance operational mode only occurs for a short period of time, but nonetheless represents about 50% of the total energy consumption because the output capacity of the resistance heater is much greater than the capacity of the HP;
- inaccuracy in the control model results in a significant underestimation of the length of the HP+resistance operational mode such that the time the resistance heater is working in practice is twice as high as the model estimate.

Despite this the COP correlation models are reasonably accurate during the HP mode, especially for the two-variable model.

Correlating variable issue

In principle COP_{ins} depends on the water temperature surrounding the condenser. Depending on the specific configuration of the HP under consideration, the water temperature surrounding the condenser may be the temperature of the inlet water, the temperature of the outlet water, or even a combination of the two. Due to a lack of appropriate experimental test data, it's been necessary to use the average tank water temperature as the correlating variable for the current study. This is likely to be an appropriate choice when the water being supplied to the condenser is drawn from the water storage tank and the water in the latter is well mixed i.e. is not stratified; and these conditions are more or less satisfied in almost all of the experimental tests investigated in this study. However, it is important to recognise that a model based on average tank water temperature is unlikely to produce reliable results for the following situations:

- When the water supplied to the condenser is drawn directly from the mains water supply (but not from the storage tank), which is true for the Korean tests. In this case, significant error could occur when the inlet water temperature differs appreciably from the tank water temperature, as occurs in Korean test n°1.
- When tank stratification occurs. In the tests studied, this phenomenon is not observed, with the exception of HPWH Model A and only at the beginning of the test (probably due to the activation of the electric resistance heater). The lack of information regarding the exact configuration of the HPWH (i.e. of the geometry of the condenser coil and location of the resistance heater in the tank) and of the inlet and outlet water temperatures does not permit an in-depth study of the impact of this phenomenon on the predictive capability of the model developed.

To avoid these problems, the tank water temperature used in the correlation model should be replaced by a more appropriate variable, depending on the specific configuration of the HPWH.

Modelling HPWH performance over a full test cycle including a pattern of draw-offs

Due to the lack of appropriate test data, the heat loss model is reduced to a simpler form which is only appropriate in specific conditions (ambient air temperature constant, little variation of the tank water temperature). In order to generalize the methodology for other conditions, a heat loss model based on Eq. 12 would need to be developed.

In addition, the proposed methodology considers that the control logic is the same in all operational modes (heat up, stand-by with or without draw-offs). While this is relatively true for HPWH Model B, the method may not be appropriate for a HP that uses different control logic dependent on the operational mode. For example, the case when full-load control is used in the heat-up phase and part-load control in the stand-by phase. Additional information on the control system (frequency control, cyclic operation control) used by the specific model of HPWH would then be required to simulate the overall COP. This poses a particularly difficult challenge due to the range of differing part load circuitry and control logics used by different manufacturers and it seems unlikely the control logic could be deduced from experimental data. Thus, this limitation could only be overcome if information about the part load circuitry and control logic were to be made available by the manufacturer. In principle, the provision of such information could enable the development of performance models allowing reliable performance prediction over a full test cycle including draw-off patterns.

C10. Conclusions

This report examined the potential to model HPWH energy performance. A simulation methodology applicable to the heat-up phase was presented wherein models of instantaneous COP were developed using regression techniques. The average COP performance for a standard test was then calculated and compared to the measured values. Three correlation models based on two, three or four-variables were examined. For each of these two cases, depending on the time period used to average the data used for the correlations (1 minute or 5 minutes, corresponding roughly to tank water temperature variations of 1 K or 5 K respectively), were derived and tested.

This method was tested with the results of all four of Test Conditions in AS/NZS 5125, for HPWH Models B and C. The performance models obtained were then use to estimate the COP that would be expected when the same water heaters are tested in accordance with other national standard test procedures and the estimates were compared to experimental data measured for the water heaters tested under these other standards; specifically the heat-up phases of the US, Japanese and European test standards and the steady-state Korean test standard. The simulation results produced are in close agreement with the measured data.

The method was also used to simulate performance over a full test cycle including a draw off pattern. This required an electric power model and a heat loss model to be developed in addition to the COP model. These models allowed evolution of tank water temperature over time to be determined. The resulting simulations had acceptable errors when compared to the measured values.

It can therefore be concluded that the models developed from the AS/NZS tests give accurate predictions of the HPWH COP during the heat-up phase when used to make estimates of the COP expected when the HPWH is tested under other international test standards, and thus could be used to avoid the need to carry out additional physical tests for those standards.

There were no significant differences between the results obtained from the two types of data sets (i.e. the models based on water temperature intervals of 1 K or 5 K). The two-variable model gives the best results on average, compared to the three and four-variable models, which is due to the dry bulb and dew point air temperatures used to derive the models being highly correlated.

The limitations of the methodology proposed were also discussed, specifically regarding; the difficulty in modelling a hybrid system (heat pump + electric resistance heater), the choice of regression variables used in the model and the potential to model COP performance over a full test cycle including a water draw-off pattern.

Due to limitations in the experimental data used to derive the models, the average tank water temperature was used for all the HPWHs tested, resulting in important errors for some operating conditions. In general it is recommended that a better-adapted variable be used dependent on the specific configuration of the HPWH, providing that appropriate experimental data is available.

For hybrid systems (electric resistance heater plus heat pump), the data analysis proposed is unlikely to lead to a reliable performance model. The main difficulty is due to the unknown control logic used to command the operational modes.

Modelling performance during a full test with draw-off pattern requires a number of factors to be considered. While in principle the heat losses of the storage tank can be modelled without undue difficulty, the part-load performance of the heat pump and its control logic are unknown. Even though the proposed methodology was found to work for the HPWH Models B and C operated under the US test standard conditions, it is strongly recommended that the method be tested with other systems where the control logic is known in order to clarify the energy performance impact of the control logic, which may vary across different operational modes.

Annex A. Operating conditions for the HPWH Model B tests

Test Standard (and test number/type)			**Air temperature**		**Average water temperature**		**Draw off cycle**		
			dry bulb	**wet bulb**	**at the beginning of test**	**at the end of test**	**flow rate**	**inlet water temperature**	**outlet water temperature**
AS/NZS		***1***	10	9	9.5	58.4	No		
		2	20	16	14,.6	57.4			
		3	35	23	24.4	54.8			
		4	35	29	24.3	54.2			
US			19.7	13.5	A	A	NA		
ES			19.9	14.5	A	A	NA		
KS	***Space heating tests***	***Standard***	7	6	A	A	A	A	NA
		Low temperature	2	1,1	A	A	A	A	NA
		Winter season	-7 (?)	-7 (?)	A	A	A	A	NA
		Cold zone temperature	-15 (?)	-15 (?)	A	A	A	A	NA
	Hot water tests	***Standard***	7	6	A	A	A	A	NA
		Cold zone temperature	-15 (?)	-15 (?)	A	A	A	A	NA
JIS			16	12	A	A	NA		

Table 15. Test conditions in different test standards (values collected from the raw data of HPWH

Model B tests). Where: A = data is available, and NA = data was not recorded, but is still necessary to calculate the COP and to develop a reliable performance model; (?) = data is seemly incorrect

Annex B. Performance modelling results for HPWH Model C

The calculation approach presented in Section0 was also applied to experimental data for HPWH Model C. Figure 35 shows the estimated values produced by correlation models derived under the different scenarios, compared with the measured experimental data. Figure 36shows the error ε as defined in Eq. 11 for each of these models. In a number of cases the error is very high, especially compared to the results obtained with HPWH Model B (see Figure 23). The most likely cause is because of the unreliable data used. For example, mistakes are noted in the air temperature measurement for the AS/NZS test n°3 where the dry bulb and wet bulb temperatures are reported to give the same value. However, in order to allow calculations to proceed using this data, it was assumed that the wet bulb temperature attains -8 °C, the value required by the standard.

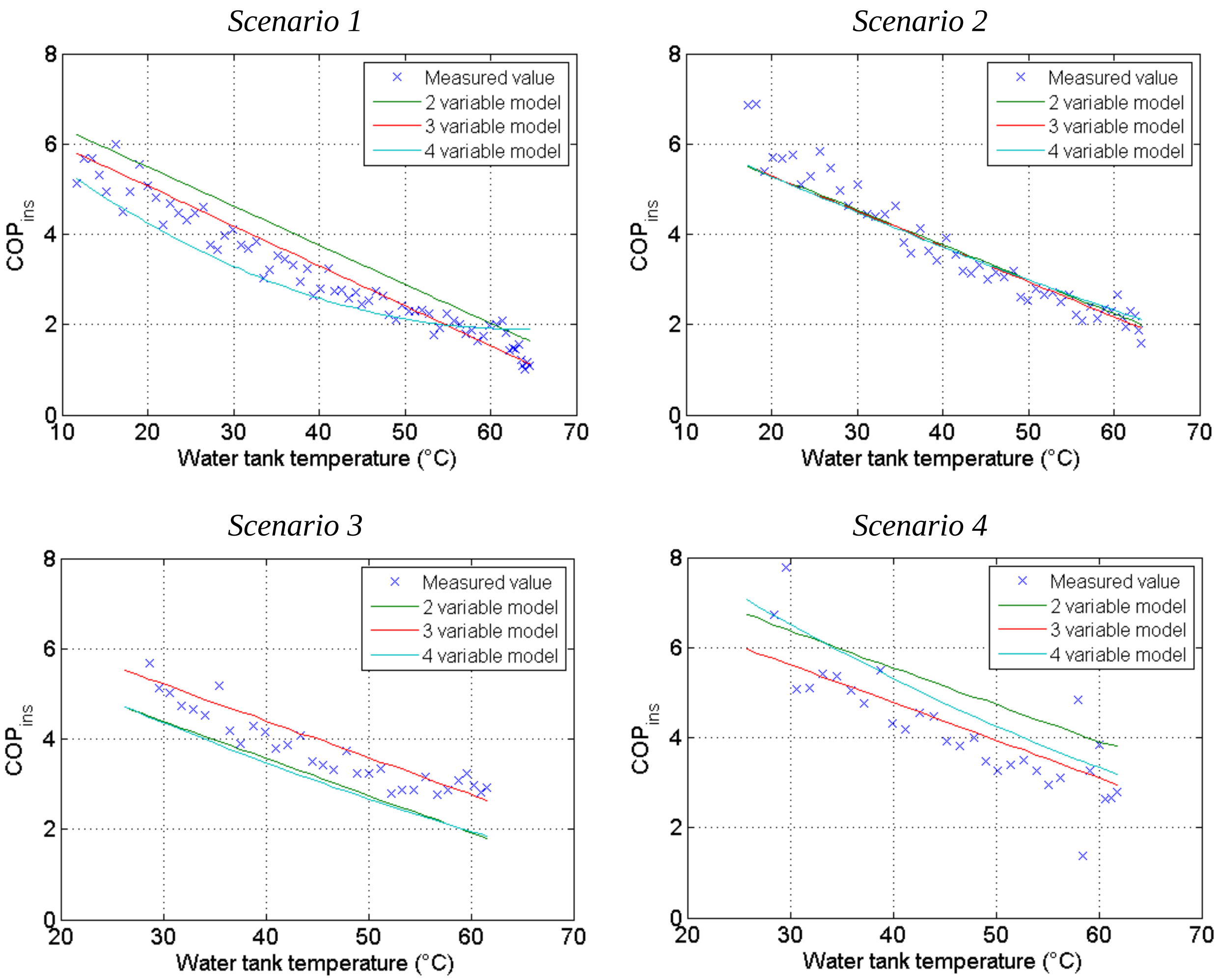
Scenario 1 *Scenario 2* *Scenario 3* *Scenario 4*

Figure 35. Predictive capability of the correlation models of HPWH Model C (built from 1-minute interval data), in different scenarios

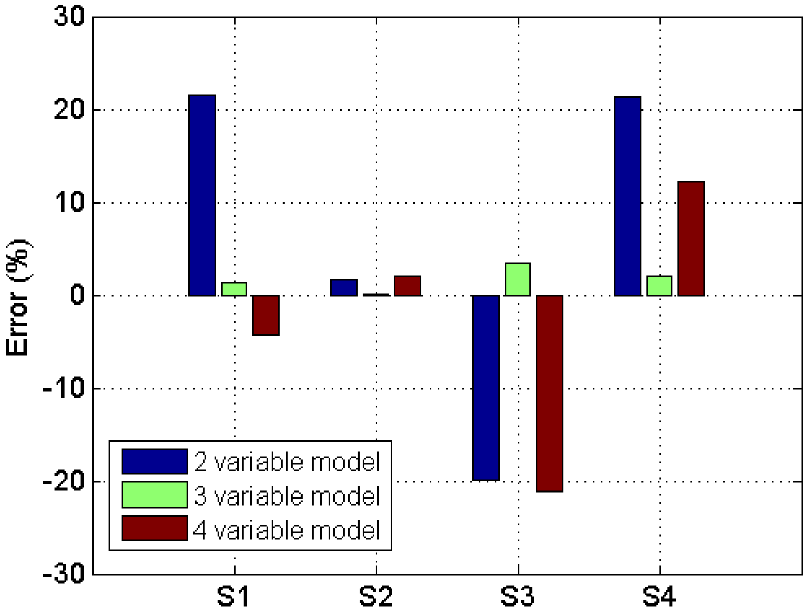

Figure 36. Error of COP_{int} predicted, compared to the measured values (in the case of HPWH Model C)

Because of the unreliable data found in AS/NZS test n°3, only three other sets of test data are used to develop the correlation models. The latter are then compared to the heat-up phases of the Japanese, European and USA standard tests. The results are shown in Figure 37 and illustrate the predictive capabilities of all three models studied

The models obtained are also compared to the Korean test standards where the HP is under steady state conditions[37]. The predictive error is shown in Figure 38. The same phenomena that occurred with modelling of the HPWH Model B is observed with HPWH Model C, i.e. that the predictive capability is relatively good in all cases, except for the Korean standard test n°1 (due to the large difference in the water tank temperature and the temperature of the water supplied to the condenser).

The same methodology presented in Section C6 is applied to the HPWH Model C. In particular, the AS/NZS test standard experimental data is used to build COP and electric power regression models. The control model is obtained through analysis of a stand-by period in the test data (Figure 39). From which, it is assumed that the start/stop time is controlled in such a manner that the water temperature remains within the temperature interval of 53°C to 56 °C. In addition, four cooling cycles, extracted at random from the US standard test data, are used to determine the heat loss model and are used to produce the results shown in Figure 40. From this it is determined that $C_{loss} = 0.028$ K/min.

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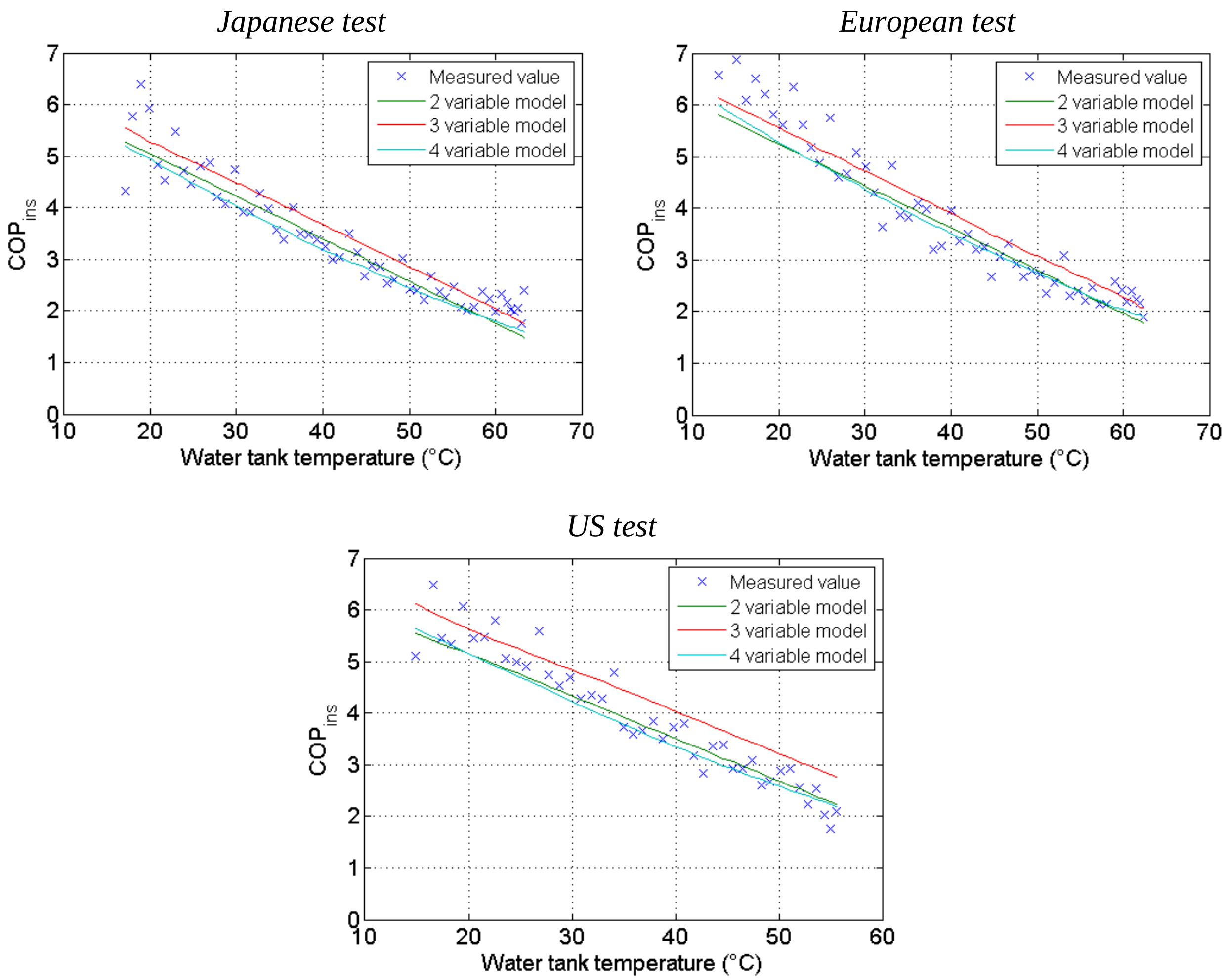
[37] Only three sets of Korean Standard test data are used in this comparison due to the lack of reliability ofall the data sets, such that tests where the dry bulb and wet bulb measurements were the same value are excluded.



Japanese test

European test

US test

Figure 37. Predictive capability of the correlation models compared to measured data for three different test standards (HPWH Model C)

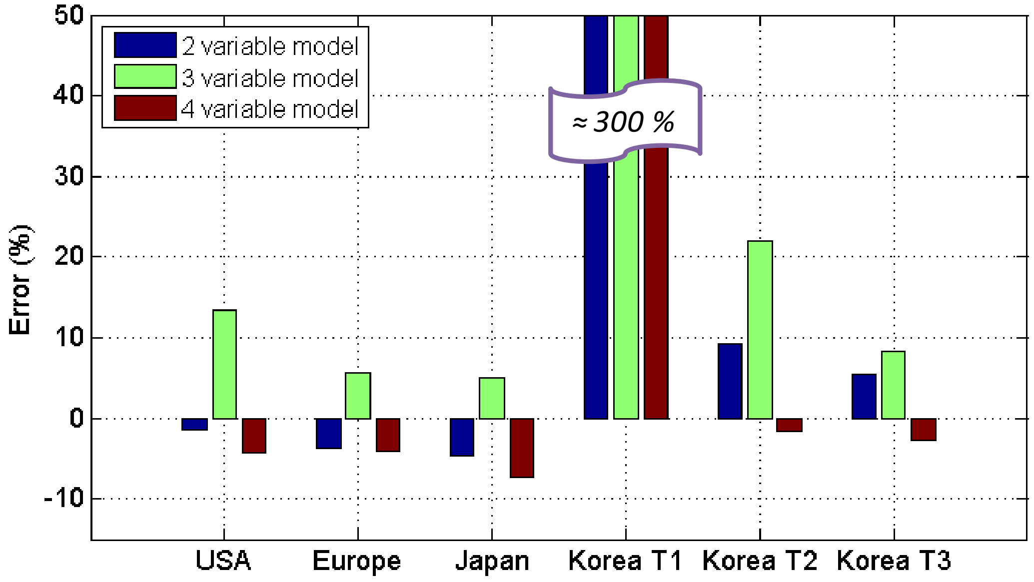


Figure 38. Error in predicted COP_{int} for various standard test procedures (HPWH Model C)

Figure 41 shows the evolution of the tank water temperature over time (both the simulated values and the experimentally measured values). The simulated values are generally close to the measured values, especially in the heat up period. The differences observed in the "stand-by with draw" period are due to the differences in the measured versus predicted start/stop times and show that the simulated control model is not fully consistent with the actual control during this period (the set point temperatures used in the model are lower than the ones measured in the draw-off period). This may be due to a change in the control operations (logic) applied for this phase, but it is more likely that the average tank temperature does not properly represent the real controlled variable under dynamic conditions. The delay observed in the "stand-by without draw" period is also due to the fact that the control model used is not completely accurate.

Table 16 compares the simulation results with the measured values. During the heat up phase, the heat up energy predicted by the simulation is underestimated due to the fact that the set point temperatures used in the simulation are lower than the measured ones. However, as this bias also affects the electric power, the resulting predicted COP is remains very close to the measured one with an error of only 0.6 %.

During the "stand-by with draw" period, the same phenomena is observed, i.e. both the delivered heating energy and electric power are underestimated, resulting, however, in a satisfactory COP prediction (having an error of 2.9 %) even though the errors related to the electricity consumption and heating energy are relatively high.

During the "stand-by without draw" period, the temperature loss is estimated correctly, which indicates that the heat loss model is accurate. However, the estimated electricity consumption is much lower than the measured value. This indicates that the HP performance is worse in this phase than in the heat up phase, probably due to the difference in the control logic previously commented on and possibly because of the impact of cycling (which could degrade the performance when compared to the steady state model for the same water and air temperature conditions).

The error in COP over the whole test is 14.2 %, mainly due to the relatively large error in the predicted electricity consumption in the "stand-by without draw" period.

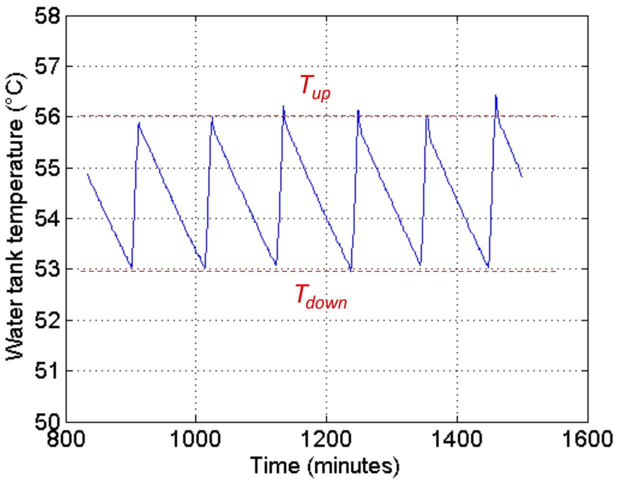
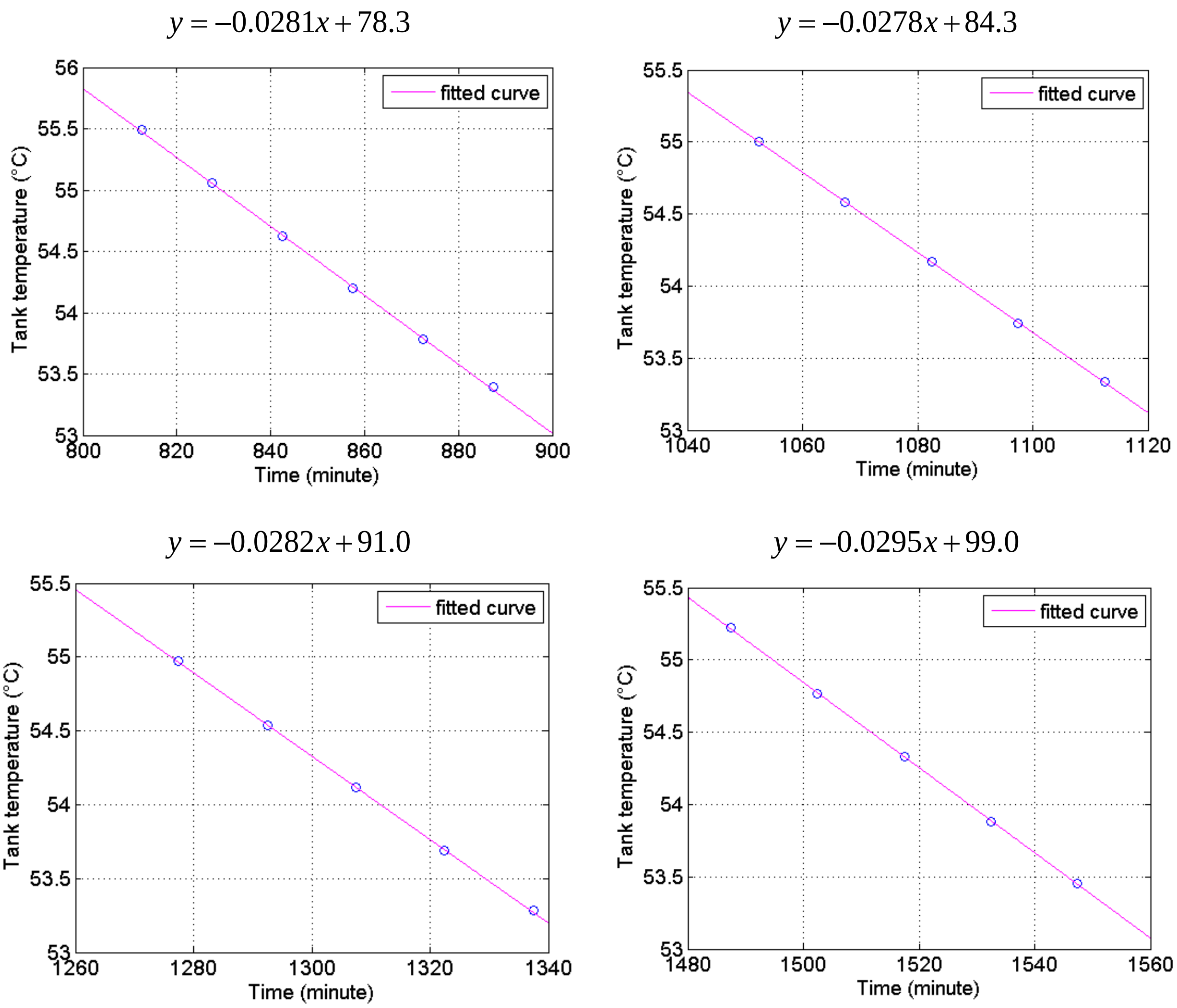


Figure 39. Evolution over time of the tank water temperature during a stand-by period (HPWH Model C)



$y = -0.0281x + 78.3$

$y = -0.0278x + 84.3$

$y = -0.0282x + 91.0$

$y = -0.0295x + 99.0$

Figure 40. Evolution over time of the tank water temperature for different cooling cycles (HPWH Model C)

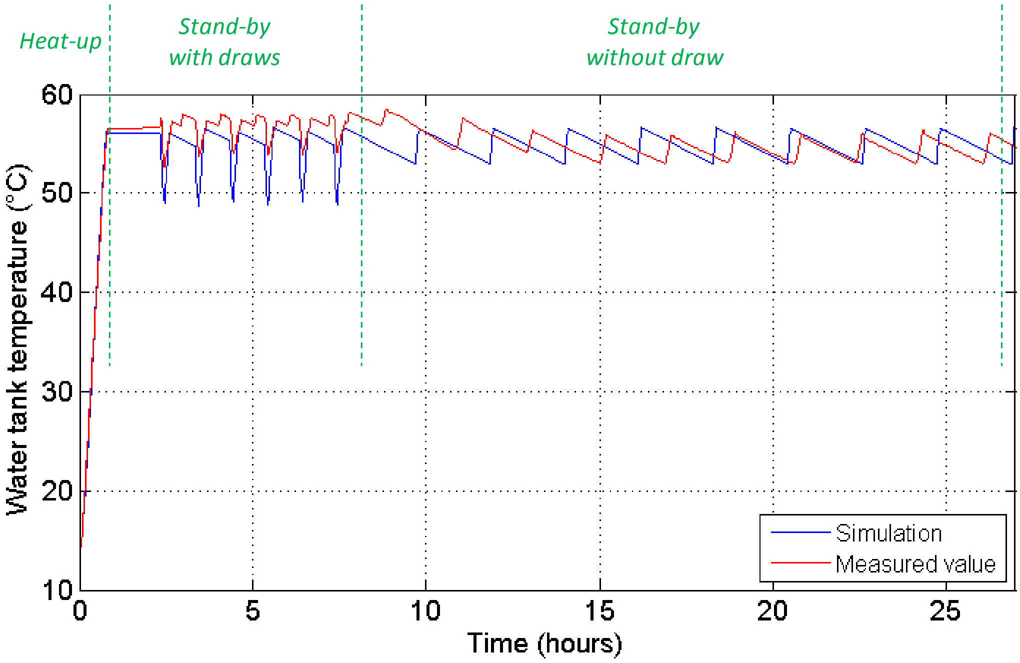


Figure 41. Predictive capability of the model developed under US test standard conditions (HPWH Model C)

		Simulated	*Measured*	*Error (%)*
Heat up phase				
Electric consumption	MJ	9.9	10.2	-3.2
Heating up power	MJ	35.9	36.9	-2.7
COP	-	3.6	3.6	0.6
With draw stand-by phase				
Electric consumption	MJ	22.3	25.9	-13.8
Energy of the drawn water	MJ	46.9	52.8	-11.3
COP	-	2.1	2.0	2.9
Without draw stand-by phase				
Electric consumption	MJ	12.2	18.8	-35.4
Temperatureloss	K	33.1	32.8	0.8
Whole test				
Electric consumption	MJ	44.3	54.9	-19.2
Heating energy	MJ	82.7	89.7	-7.7
COP	-	1.9	1.6	14.2

Table 16. Comparison of simulation results with measured values in different operational phases (HPWH Model C)

Annex C. Correlation of dry and wet bulb temperatures under standard test conditions

Although temperature and humidity (expressed via the wet bulb temperature) are not generally correlated in real life operating conditions, they are for the standard test conditions used to test HPWHs (Figure 42).

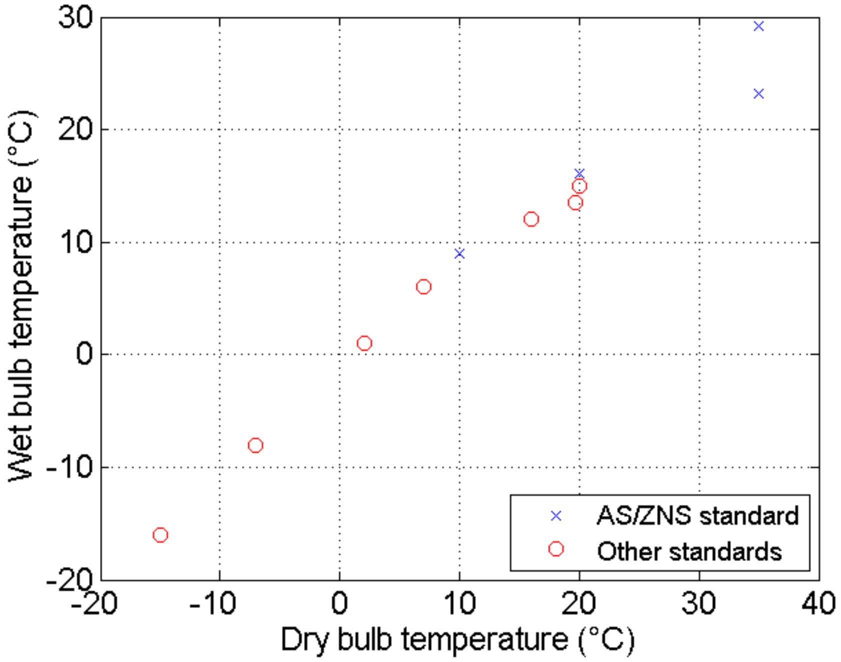


Figure 42. Coincident wet bulb and dry bulb temperatures of the different standard tests in this report (HPWH Model B)

When comparing the predictive performance of two-, three and four-variable models described in section 4, it should be kept in mind that the three- and four-variable models include two separate variables to represent both the outdoor air temperature and humidity(either the wet bulb or dew point temperature and the dry bulb temperature). However, under the specific test conditions of the different international test standards these paired variables are highly correlated. This explains why the two-variable model appears to give a slightly better fit to the test standard data even though in real life situations the three- and four-variable models may be more accurate.

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Appendix D: Project Workshops

Beijing, April 2013

Date: Friday 12 April 2013, 13:30-17:00
Following 41st Meeting of APEC Expert Group on Energy Efficiency and Conservation (EGEEC)

Location: North Star Continental Grand Hotel, Beijing, China
No.8 Beichen Dong Road, Chaoyang District, Beijing, P.R.China

Organiser: Collaborative Labeling and Appliance Standards Program (CLASP) and International Copper Association (ICA)
Contact for Registrations: Mr Wei Bo (weibo@csc.org.cn).

Time	Session	Speaker
13:00 to 13:30	Registration	
13:30 to 13:45	Welcome and introduction	Ms Anna Lising, CLASP
13:45 to 14:15	Overview of project	Dr George Wilkenfeld
14:15 to 15:00	Analysis of existing heat pump water heater test standards; First results from KTL tests	Dr George Wilkenfeld
15:00 to 15:30	Coffee break	
15:30 to 15:45	Chinese manufacturers' experience with international test standards	Li Caixia Director, Planning Department Haier Water Heater Co Ltd
15:30 to 16:15	A way forward- selective testing and computer simulation?	Dr George Wilkenfeld
16:15 to 17:00	Questions and discussion	Ms Anna Lising, CLASP

ECONOMY	**Name**	**Company/Organization**
New Zealand	Mr.Terry Collins	General Manager Products Energy Efficiency and Conservation Authority (EECA)
New Zealand	Mr.Martin Brown-Santirso	Advisor Transport Energy Efficiency and Conservation Authority (EECA)
People's Republic of China	Ms.Zhang Shaojun	Director , China Standard Certification Center（CSC）
USA	Dr.Cary Bloyd	Senior Staff Scientist Pacific Northwest National Laboratory
The Republic of Korea	Ms.Eunsun Do	Staff, Korea Energy Management Corporation (KEMCO)
Australia	Dr.George Wilkenfeld	Director, GeorgeWilkenfeld & Associates, Energy Policy Consultants
Regional	Mr.Pierre Cazelles	Director, International Copper Association(ICA)
USA	Ms.Anna Lising	Senior Associate, CLASP
Hong Kong, China	Mr.Ping-ho Cho	Engineer, Electrical and Mechanical Services Department, Government of Hong Kong SAR

Japan	Dr.Kazutomo IRIE	General Manager Asia Pacific Energy Research Centre
Chinese Taipei	Mr.Shin-Hang Lo	Senior Project Manager Industrial Technology Research Institute
Indonesia	Mr.Harris	Deputy Director Ministry of Energy and Mineral Resources
USA	Mr.Derek Greenauer	Manager Uunderwriters' Laboratory
Thailand	Dr.Pongpan Vorasayan	Engineer Department of Alternative Energy Development and Efficiency
Thailand	Ms.Patlada Sinsap	Plan and Policy Analyst Ministry of Energy
Chinese Taipei	Mr.Zi-Hong Chang	Associate Technical Specialist Bureau of Energy, Ministry of Economic Affairs
Australia	Dr.Tim Farrell	Director Department of Climate Change and Energy Efficiency
Japan	Mr.Hiroei Mikami	Researcher Daikin Industries, Ltd.
People's Republic of China	Mr. Wei Bo	Director , China Standard Certification Center（CSC）
People's Republic of China	Mr.Zhao Dengjun	Senior Manger, Panasonic R&D Center China Co., Ltd
People's Republic of China	Mr.Yu Yang	Research Associate, CLASP
People's Republic of China	Mr.Li Jiayang	Technical Associate, CLASP
People's Republic of China	Mr.Zhang Xinhang	Director, Panasonic Appliances Air-Conditioning(Guangzhou) Co.,Ltd
People's Republic of China	Mr.Tian Xiaoling	Director, Panasonic Appliances Air-Conditioning(Guangzhou) Co.,Ltd
People's Republic of China	Mr.Chen Huaze	Manager, Shenzhen McQuay Co.,Ltd
People's Republic of China	Mr.Luo Weijie	Manager, Shenzhen McQuay Co.,Ltd
People's Republic of China	Mr.Jin Yunlin	Manager, Clement strapdown Refrigeration Equipment (Shanghai) Co., Ltd.
People's Republic of China	Mr.Lin Xiaodong	Manager, Panasonic Wanbao Appliances Compressor (Guangzhou) Co.,Ltd.
People's Republic of China	Mr.He Guancheng	Manager, Vkan Certification and Testing Co., Ltd.
People's Republic of China	Ms.Qi Yun	Manager China Household Electric Appliance Research Institute
People's Republic of China	Mr.Zhang Ziqi	Manager China Household Electric Appliance Research Institute
People's Republic of China	Mr.Huang Zhibo	Manager Guangdong Chigo Air Conditioning Co., Ltd
People's Republic of China	Mr.Zhang Jianqiang	Manager , Shanghai Daikin Co.,Ltd
People's Republic of China	Mr.Zhu Fenglei	Director, Hefei General Mechanical and Electric Product Inspection Institute
People's Republic of China	Ms.Li Caixia	Director, Planning Department Haier Water Heater Co, Haier Group
People's Republic of China	Mr.Dong Shi	Senior Engineer, Haier Water Heater Co, Haier Group
People's Republic of China	Mr.Zhang Xiaoquan	Manager, Air Conditioning Product Director Europe Market, Haier Group
People's Republic of China	Mr.Chen Jun	Manager, China CEPREI Laboratory
People's Republic of China	Mr.Chen Rong	Manager, Shanghai Institute of Quality Inspection and Technical Research

Coimbra, September 2013

Date: Tuesday 10 September 2013, 13:30-17:00
Side event preceding the 7th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL, University of Coimbra, Portugal, 11-13 September 2013)

Location: Faculty of Sciences and Technology (FCTUC), new Coimbra University (Pólo II)

Organisers: Collaborative Labeling and Appliance Standards Program (CLASP) and the International Copper Association (ICA)

Contact for Registrations: pierre.cazelles@copperalliance.asia

Time	Session	Speaker
13:00 to 13:30	Registration	
13:30 to 13:45	Welcome and introductions	Steve Pantano, CLASP
13:45 to 14:15	Overview of project	George Wilkenfeld, lead consultant
14:15 to 14:40	Analysis of existing heat pump water heater test standards	Lloyd Harrington, Energy Efficient Strategies
14:40 to 15:00	KTL experience with existing heat pump water heater test standards	Jun Choi, Korea Testing Laboratory (KTL)
15:00 to 15:20	Coffee break	
15:20 to 15:50	A way forward- selective testing and computer simulation?	Paul Waide, Waide Strategic Efficiency Philippe Riviere, ARMINES
15:50 to 16:10	Heat pump tests standards in USA	Jim Lutz
16:10 to 16:30	Lessons learned, and next steps	George Wilkenfeld, lead consultant
16:30 to 17:00	Questions and discussion	Steve Pantano, CLASP

ECONOMY	**NAME**	**ORGANIZATION**
USA	Jim McMahon	Director Better Climate Research & Policy Analysis
Republic of Korea	Jun Choi	Chief Researcher Republic of KOREA
South Africa	Adiel Jakoef	SUMV Team Manager Stellenbosch University
Australia	George Wilkenfield	Director George Wilkenfeld & Associates
Australia	David Whaley	Research Associate University of South Australia
Australia	Lloyd Harrington	Director Energy Efficient Strategies
USA	Mr. Vijay Earanky	Sr. Electronics Engineer Regal Beloit Corp

USA	Dr. Nihar Shah	Scientist, Engineering Associate Lawrence Berkeley National Laboratory
Italy	Dr.Lorenza di Pilla	Phd student University of Cagliari
Portugal	Mr. Pedro Adao	Sr. Specialist, Innovation & Engineering EDP Comercial, S.A
Switzerland	Ms. Zaira Girbau Garcia	Topten Latin America Coordinator Topten International Services
USA	Stephen Pantano	Senior Director of Global Programs CLASP
Australia	Mr. Justin McMillan	Administration Manager Siddons Solarstream Pty Ltd
Italy	Dr. Angelo Mancini	Labs Coord., Cert., Reg. Ariston Thermo SpA
USA	Mr. Alan MEIER	Scientist, Building Technologies Lawrence Berkeley National Laboratory
USA	Mr. Steve Kukoda	Vice-President International Copper Association
USA	Mr. Ajit Advani	SEE Global Team Leader International Copper Association
UK	Dr. Paul Waide	Director Waide Strategic Efficiency Ltd
Portugal	Dr. Anibal Almeida	Director Institute of Systems and Robotics, ISR-DEEC-Pólo II – Universidade de Coimbra
Austria	Mr. Martin Reder	Ochsner Warmepumpen GmbH
Portugal	Dr. João Ramos	Professor Mechanical Engineeing Polytechnic Institute of Leiria
Portugal	Ms. Anabela Carvalho	Phd student University of Coimbra
China	Mr. Pierre Cazelles	Director, Partnerships Asia International Copper Association
Portugal	Mr. Joaquim Delgado	Professor ESTGV
USA	Mr. Michael McNeil	Lawrence Berkeley National Laboratory
USA	Mr. My Ton	CLASP
France	Mr. Philippe Riviere	Center Director Ecoles des Mines, Paris