Public summary report

A dynamic heat pump test and development facility

TNO Public ⟩ TNO 2023 R11570
29 August 2023

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Classification report	TNO Public
Title	TNO Public
Report text	TNO Public
Number of pages	13 (excl. front and back cover)
Number of appendices	0
Sponsor	Rijksdienst voor Ondernemend Nederland (RVO)
Programme name	Integrale Energietransitie in Bestaande Bouw (IEBB)
Project name	A dynamic heat pump test and development facility
Project number	060.42972/01.04

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1 Introduction

Low-carbon heat generators such as heat pumps and hybrids[1], and their combination with heat emitter systems and building heating loads, are more sensitive to operating conditions than traditional heating systems such as boilers. More insight into the real-world performance of such systems can be very useful for product manufacturers, installers, product specifiers, building owners and policy makers in order to make informed decisions regarding product design, specifying and commissioning systems and understanding energy use. The typical method for obtaining real-world performance data is a field-trial with a real building and climate control equipment, along with data acquisition systems. Subject to data quality, the data is real, so removing assumptions such as how a product is expected to operate, and can be very insightful. However, field-trials have several drawbacks. They are seasonally dependent so data collection is potentially delayed and there is no certainty that a particular period of interest shall occur. Many variables, in particular weather conditions, cannot be controlled so reproducibility is poor and multi-variable data noise can impact the result, making analysis more challenging. Some parameters can be difficult to measure, such as occupancy and ventilation. For practical and possibly cost reasons there is also a limit to what can be measured.

Laboratory testing methods for determining heat pump performance exist, such as EN14511. Heat pump testing according to this standard involves performance testing at predescribed static conditions with fixed or limited inverter speeds, and heating system controls inactive. Related standards such as EN14825 take data obtained from the lab measurements and apply to calculation procedures to determine outputs such as seasonal Coefficient of Performance (SCOP). However, they ignore the effect of dynamics and variation of control behaviour, making these methods less representative of real world performance. The underlying assumptions can be rather idealised, such as assuming that the heat output perfectly matches the heat demand, the house is maintained at a constant target temperature and the control functions are as would be desired with no unexpected consequences. For products such as hybrid heat pumps the control realities become even more important as extra degrees of operating freedom are provided by the addition of the boiler.

These standard test and calculation methods are commonly used for product performance ratings and building energy performance calculations, where test method and calculation simplicity allow for relatively easy accessibility for market stakeholders. This is achieved at the expense of excluding factors that can strongly affect real world performance. There is thus a need for an alternative test method for heat pumps and similar systems such as hybrids. In this project a dynamic heat pump test- and development facility (also referred to as the "Emulator test facility") was created and this summary report describes the facility and its use.

[1] A hybrid heat pump is a combination of a (relatively small) air to water heat pump, used for space heating and a gas fired boiler for supplementary heating and domestic hot water production.

2 Facility development

The developed test facility is based on the hardware-in-loop principle whereby dynamic tests are carried out by combining real hardware in a laboratory setting, such as heat pumps, hybrids, buffer vessels etc, with computer models of a house and hydraulic heating system. These two hardware and model sub-systems are interfaced to exchange real-time information related to performance, react accordingly and outputs of each sub system are transferred to the other. This allows for the hardware (heat pump) to react to a varying heat demand and at varying temperatures, imposed by the software (house and heating system). The core principle of the emulator is that the tested (hybrid) heat pump behaves as it would when applied to the real (modelled) system.

For this the following hardware is required for interacting with the heat pump, represented in simplified form in Figure 1:

- *Climate chamber.*
  The climate chamber provides ambient conditions (temperature and humidity) for an air source heat pump. Some systems also depend on an external temperature sensor for its control logic, as measured in the same chamber.
- *Heat rejection circuit.*
  The heat generated in the form of hot water is normally delivered to a heating circuit such as radiators. This connection needs to be emulated and for this a purpose-built circuit is used. This circuit cools (or heats) the return water to the heat generator to a temperature which is defined by the computer model of the heating circuit. Additionally this circuit alters its hydraulic resistance as determined by the model, as it would vary when using thermostatic radiator valves.
- *Interface of the room thermostat with the indoor temperature of the model.*
  The heat pump controller provided with the product usually functions as a room thermostat, meaning that the controller has an internal temperature sensor which it can use for room temperature control feedback. To ensure proper operation of the system, the thermostat should read the correct room temperature. In the emulator the real reference sensor is removed and replaced by a virtual sensor, which emulates a temperature coming from the house model at the assumed controller location.

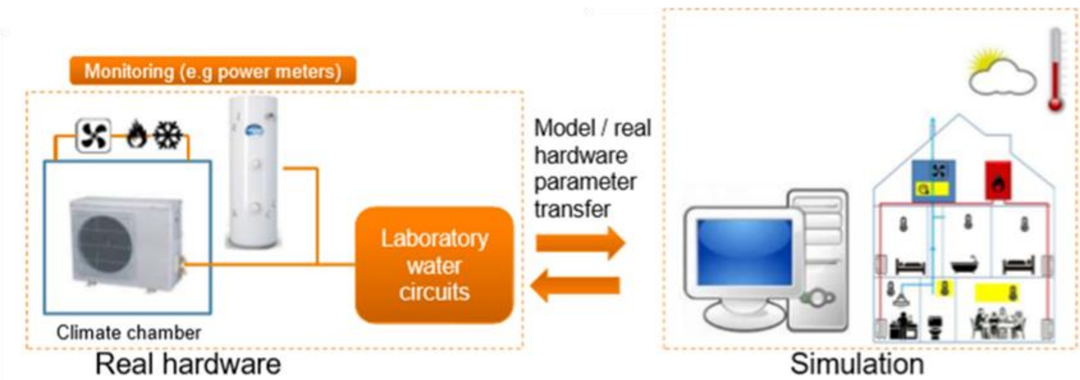

Figure 1. Representation of emulator test facility

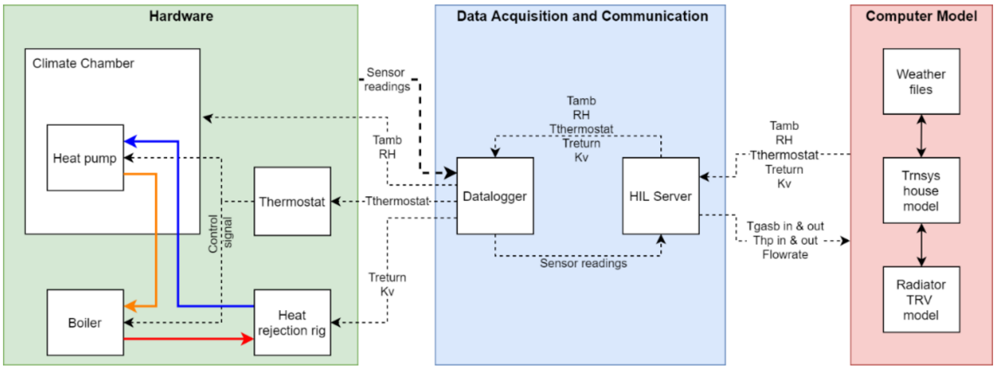

Figure 2. Schematic diagram of the emulator structure containing the hardware: air to water heat pump, climate chamber, heat rejection and software environments and parameters exchanged between them.

The general structure of the entire emulator is given schematically in Figure 2. The system consists of mainly three parts.

Hardware (left of Figure 2)

The climate chamber containing the heat pump has a remote control input for temperature and humidity setpoint so the climate chamber can follow the simulated weather file. The design and control of the chamber is very important to ensure the correct test results since ambient temperature is a parameter used by various aspects of unit control algorithms. For example, ambient temperature determines the target heating water temperature via a weather compensation curve ('stooklijn'). It is also used in the logic related to changeover between boiler and heat pump operation.

High humidity is a challenge for the operation of air source heat pumps at ambient conditions below around 2-4°C. If the temperature of the evaporator surface drops below 0°C, condensation and frost can occur on the heat exchanger resulting in airflow blockage. Heat pumps will detect excessive ice and initiate a defrost cycle. From the chamber perspective the heat pump rapidly switches from a heat/moisture sink to a source so there is a near-step change in chamber conditioning requirements. It is important that the chamber is large enough and that the temperature and humidity control is working well so that the chamber is able to minimise the impact of disturbances such as defrosting and heat pump cycling which may potentially cause unrealistic unit control actions.

The high humidity is not only a problem for the heat pump. The climate chamber air handling unit cooling coils can also frost up at low temperature/high humidity but must continue to operate for a whole test duration while maintaining conditions. The new TNO climate chambers are specifically designed to allow long term operation in these conditions which makes them ideal for testing heat pumps under realistic wheather conditions. This is especially relevant for emulating scenarios for the Dutch climate which typically has a higher winter humidity compared to assumptions in European test standards.

Data acquisition and Communication (middle of Figure 2)

The Hardware-in-Loop (HIL) server is a program which acts as a library for data. It can be approached by any other software which can store or retrieve data. This is required to operate the various hardware and software components on independent time steps without the need of exactly synchronising data acquisition and model execution. It serves the important role as the overall synchronisation manager of the setup to ensure all aspects of the setup operate according to the same simulated time so ensuring that no time divergence occurs, according to, for example, different datalogger scan times, changing model calculation times due to background CPU processes etc.

The datalogger software is used to interact with all the laboratory-grade data acquisition hardware and electrical power analysers. Plug-ins are developed to enable the house model and data acquisition to interact with the HIL-server.

Computer model (right of Figure 2)
The house model uses TRNSYS which is a commercial software package intended for modelling thermal energy systems and is often used for building simulations. The house model interacts with a TNO-developed model for the heating circuit and reads weather files to determine the heating demand of the house. The house model is a dynamic, multi-zone model. Several house models are available, among which a 1970s terraced house is used. To create an accurate house model, the building physics, ventilation and infiltration, internal gains, weather and solar gains are carefully defined. The intention of the model is to create a common house with representative heat loads and response dynamics. The dynamic response was validated against monitored data from similar houses.

The house is heated by a water-based radiator system which is (originally) supplied from a gas boiler, but the heat generator is substituted by the real test hardware. The heat emitters (radiators) in the house are modelled in a separate model coupled to the house model. Since the radiators are directly coupled to the hybrid heat pump their behaviour is important to the working of the system. The heat emitter models closely mimic the characteristics measured in previous TNO heat emitter tests. Reverse-cycle heat pump behaviour during defrosting was also included as the radiator behaviour during this process is known to be different from steady state heating.

The 1970s terraced house with a radiator heating system is one of the most common house typologies in the Netherlands.

3 Application – hybrid heat pumps

Approach
The central research question is:
Is the emulator test facility of added value in testing sophisticated heating systems, in particular hybrid heat pumps?

With the following sub-questions:
1. Can we obtain a better understanding of the emulator test facility from actual tests, identify limitations, and suggest improvements where possible?
2. Can we demonstrate the value of dynamic, system level testing over static product-based tests? This may take the form of observing unexpected control behaviour or more general deviation from the "classic" assumed behaviour.
3. Can we demonstrate that the facility can be used to repeat tests under identical conditions and with controlled variations such as changing a control setting or building characteristic?
4. Can we gain insight into the real-world performance of hybrids in a typical (retrofit) use case?

To answer the research question and the sub-questions, four off-the-shelf hybrid heat pumps from different manufacturers were tested in combination with the simulated 1970's house and heating system, using a set of different 'test days' for weather conditions.

Several features make hybrids an interesting case for testing:

1. The installer / user setting of controls and the internal logic of hybrid controllers is expected to make a relatively large impact on real-use performance. Controls are a specific area where the test facility can provide insight.
2. Hybrids have more operating variables compared to boilers or stand-alone air source heat pumps and their operation may be highly dynamic.
3. Compared to boilers and heat pumps, hybrids are relatively new in the market. It is possible that there is still much to learn about their use to which our test facility can contribute.
4. Hybrids are typically used in retrofitting of houses that have not necessarily undergone extensive renovation. This is a somewhat different case to the new build scenarios which are typical for heat pumps, i.e. well insulated houses with underfloor heating, which are less dynamic and for which a lot of data is already available.

The last point is particularly relevant to the setup of this study. The intention is to create a realistic system installation, not an idealised one that may rarely be achieved. The manufacturer project partners were each invited to select a product from their range that they would recommend for the (unrenovated)1970's house and to commission the test unit in the laboratory according to their recommendations. In principle, the test facility is able to provide a lot of potentially useful information about the house and its heat emitter system, such as the house heat loss at a given outdoor temperature, installed radiator capacity, hydraulic resistance of the heating system etc. However, for retrofits this information is usually not available to an installer. Therefore only information was provided to the manufacturer project partners that would be available via a visual inspection combined with some basic knowledge about house construction and discussion with a moderately informed resident such as whether the house has ever been insulated. The resulting commissioned units were therefore different in several aspects over which the installer sometimes has control:

1. Weather compensation curve (stooklijn).
   This is typically set via selection of pre-set curves, or by manual definition of the line. Note that at -10°C ambient temperature, the maximum heating water temperature set for the test units varied between 55-75°C, which is a significant difference in the operation of heat pumps.
2. Blocking of boiler and heat pump operation with respect to outdoor temperatures.
   It is possible to configure controllers such that the boiler will not operate above x°C and the heat pump will not operate below y°C
3. How the room thermostat temperature influences the target water temperature.
   Some units included functions that adjusted the target water temperature based on room temperature. However, it was not always clear how room temperature affected target water temperature.
4. Building and heating system response time.
   This is typically an empirical description rather than a numerical one, for example lightweight, slow response etc.
5. Boiler heating capacity limit.

A standard feature of all test units was the ability to set an automated control whereby the unit would attempt to minimise either running cost or CO_2 emissions. It is believed from partner discussions that this is nearly always set to minimise running cost. The project duration included a period of very significant energy price inflation and a change in the electricity to gas price ratio, although this was not replicated in the product setup except where given as a specific test case.

It is important to note that this is not intended to be a competitive comparison, resulting in a product ranking. While certain Key Performance Indicators (KPIs) such as COP can indicate a superior performance, this is for the unit as selected and configured. It may be that certain settings were sub-optimal or a particular product happens to be better suited (or not) than another for the 1970’s house. However, the results are expected to give a realistic view of what can be happening in practice and therefore what works well and what doesn’t. It should be emphasized that in most cases there was no additional information regarding the systems’ controls other than that available from the product manuals. There was no interaction with the product design engineers or software programmers.

Results of the tests

The performance of the four hybrid heat pumps suggests the products are rather sensitive to settings and internal control logic. In particular the settings and control logic related to a target heating water temperature seemed to be significant. Some products showed cycling behaviour which generally results in reduced COP of the heat pump.

There is limited evidence from the tests that the dynamic behaviour can be changed with apparently minor control setting changes. In one case the hybrid was selecting boiler operation at high ambient temperatures which did not seem a logical response. Some limited scenarios were investigated, related to improving the house energy label from E to B via thermal insulation and airtightness improvements. Also, the gas / electricity price ratios were changed. The data from the tests suggested a somewhat logical interaction between target heating water temperature and energy efficiency and thermal comfort. For instance, when the water temperature was lowered (as influenced by control settings), the COP could be slightly higher but this would be at the expense of indoor temperatures being low at certain times, affecting thermal comfort.

The performance of the hybrid heat pumps was evaluated using three KPIs: Seasonal COP, Seasonal percentage of heat supplied by the heat pump and Weighted average indoor temperature. Table 1 shows these KPIs for the four hybrid heat pumps tested. Seasonal values were calculated based on the test results in combination with a seasonal calculation using a typical Dutch heating season weather file.

Table 1: KPIs for four different hybrid heat pumps. The second number of some units denotes a variant of test scenario.

	Unit 1	Unit 2	Unit 3-1	Unit 3-2	Unit 3-3	Unit 3-4	Unit 4-1	Unit 4-2
Seasonal COP [-]	3.01	3.57	4.01	3.90	3.89	3.60	3.28	3.62
Seasonal hp percentage [%]	57.9%	64.3%	94.1%	95.0%	95.6%	100.0%	80.0%	81.2%
Weighted average indoor temperature [ºC]	19.20 *	19.86	19.29	20.31	20.32	21.28	20.15	20.54

* includes night setback period

Unit 1: Label E – Base scenario only
Unit 2: Label E – Base scenario only
Unit 3-1: Label E – Elec:Gas price ratio 2.5
Unit 3-2: Label B – Elec:Gas price ratio 2.5
Unit 3-3: Label B – Elec:Gas price ratio 2
Unit 3-4: Label B – All electric
Unit 4-1: Label E – Original control
Unit 4-2: Label E – Revised control

Despite rather similar hardware, there was quite some variation between the four hybrid heat pumps in the main key performance indicators of SCOP and heat pump percentage. These varied from 3 to 4 for SCOP, and around 58% to as high as 95% for the heat pump heat contribution. A more detailed analysis suggested that the performance of hybrid 1 and 2 could be improved through more appropriate control settings and / or internal logic. A control change for hybrid 4 was tested, resulting in a substantial increase in performance (especially SCOP, see the rightmost column in Table 1). The results overall suggested that hybrids applied in an unrenovated terraced 1970's house had the potential to perform quite well from a SCOP (and therefore running cost and carbon emission) perspective and an overall reduction in gas use.

In summary, not only did the tests provide insight into real-world performance of hybrids in a typical (retrofit) use case, they also clearly demonstrated the added value of dynamic testing under controlled conditions.

Repeatability

Three identical test scenarios were run consecutively as a batch. The 2°C test day with hybrid 4 was chosen as this was expected to include periods of boiler operation, heat pump operation and likely defrosting. This test day also included moderate variations in heating load due to solar gains and a reasonable increase in outdoor temperature during the daytime. The test scenario may therefore be described as quite dynamic and possibly with more opportunities for result variations to develop. The main parameters from the tests are summarized in Table 2.

Table 2. Summary of parameters evaluated over successive test runs with the same settings

	Test 1	Test 2	Test 3
Gas use [kWh]	52.3	52.2	51.9
Electric use in boiler [kWh]	0.46	0.46	0.46
Heat output of boiler [kWh]	46.6	46.6	46.5
Electric use in hp [kWh]	13.8	13.5	13.4
Heat output of hp [kWh]	43.2	42.4	42.5
COP of hp [-] (including controller)	3.11	3.13	3.17
Electric use in controller unit [kWh]	0.02	0.02	0.02
Total heat output [kWh]	89.7	89.0	88.9
HP percentage [%]	48.1	47.6	47.7
Boiler percentage [%]	51.9	52.4	52.3
Thermostat average temp. [deg C]	20.90	20.89	20.88
HP entering water temp. [deg C]	39.85	39.76	39.77
HP leaving water temp. [deg C]	43.30	43.19	43.20
HP average water temp. [deg C]	41.58	41.48	41.49

In spite of defrosts occurring in test runs 1 and 2 (but not in test run 3), the parameters as tabulated were very close between the repeated tests and repeatability is quite good.

Further development of the test facility

From the actual tests we obtained a better understanding of the dynamic test facility and we identified some aspects that offer room for improvement. The house model developed for the facility is believed to behave as expected in terms of heating energy demand and the dynamics are generally within expectations when compared to real house data. However, the thermal response of the thermostat in the living room seems towards the "fast" end of the range. It may be worth investigating this further as a (too) fast responding thermostat may result (among other issues) in additional cycling of a heat pump.

It may also be worth considering the impact of solar shading, due to fixed external features and operable blinds, as there are some cases where the resulting effect of solar gain might be somewhat diminished by occupant response. Both forms of shading may result in less daytime indoor temperature overshoot.

4 Conclusions

The main conclusions are related to the operation of the dynamic test facility

- The project resulted in the successful development of a dynamic heat pump test facility, using real heat pump products combined with realistic house and heating system models. The facility allows the inclusion of system dynamics and the response of product controls. This is a key feature of the facility which is otherwise absent in static test protocols. This can add value to product development, for example in a phase between product prototyping and field tests.
- Repeatability was tested by running three identical test scenarios consecutively as a batch. The measured / calculated parameters were very close between the repeated tests.
- From actual tests we obtained a better understanding of the emulator test facility and we identified some aspects that offer room for improvement. The house model developed for the facility is believed to behave as expected in terms of heating energy demand and the dynamics are generally within expectations when compared to real house data. However, the thermal response of the thermostat in the living room seems towards the "fast" end of the range. It may be worth investigating this further as a (too) fast responding thermostat may result (among other issues) in additional cycling of a heat pump. It may also be worth considering the impact of solar shading, due to fixed external features and operable blinds, as there are some cases where the effect of solar gain might not fully align with realistic occupant response, contributing to daytime indoor temperature overshoot.

Regarding the performance of the hybrids tested, the following may be concluded.

- The potential to use the facility to improve understanding of hybrid operation has been shown. This may contribute to better predictions of how hybrids will perform in retrofits subject to different house types, fabric renovations, existing or renovated heat emitter systems etc.
- The case study suggests that hybrids can still deliver good KPIs (SCOP and HP%) even in relatively poorly insulated terraced houses. It is still expected that performance can be better in houses that have been renovated to reduce heat losses, for example through better thermal comfort and/or higher SCOP and some limited data has shown this effect. Regardless of the specific KPIs, reduced heat losses will obviously result in lower energy use regardless of the heat generator.
- One of the hybrids performed very well, operating with more than 90% of the required seasonal heating provided by the heat pump, and with an SCOP in the region of 4. However, while the settings on the unit resulted in good KPIs the thermal comfort was on the lower end of the acceptable range. It was seen that control adjustments could be made to improve comfort (and not simply by setting the thermostat higher) with a marginal reduction in COP. Although not verified by a complete test series, the SCOP and HP% are expected to remain high.
- The performance of the other three hybrids as-installed was all reasonable, but showed some spread. The worst performing unit was believed to have been configured inappropriately and this may be partially responsible for the lower KPIs.

Furthermore, it was seen that improvements could have been made to hybrids 2 and 4 with simple changes. In the case of hybrid 4 this was demonstrated with a single control change. One hybrid was not always operating in heat pump mode for some relatively warm test day scenarios when it would clearly be expected given the high COP and adequate heating capacity for the period. An explanation could not be found for this, but is expected to be related to internal control logic.

- Settings related to how the target water temperature is calculated appear to determine the extent of heat pump cycling. Highly cyclic operation may result in sub-optimal performance, such as lower COP and maybe some noise problems based on the heat pump operating intermittently between standby and at (or near) full compressor and fan speed. Control features that can compensate the target heating water temperature based on heating load, or some proxy, may have some beneficial effect. Cycling also resulted in a varying room temperature as picked up by the room thermostat, but it was typically quite close to the setpoint so this is not necessarily remarkable from a comfort perspective.

A hybrid has the heating capacity and robustness of a gas boiler. This means that a poor performance of the heat pump can be compensated for by the boiler, so the user may never experience a lack of thermal comfort. Poor performance of the heat pump, and therefore of the hybrid as a whole, may only manifest itself in a higher (than it needs to be) energy bill. Slightly higher energy bills than otherwise achievable may not be remarkable if an occupant has little awareness of likely hybrid heat pump performance, which is probably the case in most installations. A question remains as to whether sub-optimal performance in installed hybrids is noticed.

Signature

TNO › Mobility & Built Environment › Delft, 29 August 2023

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