MISSION INNOVATION
Accelerating the Clean Energy Revolution

Innovation Challenge #7

Affordable Heating & Cooling for Buildings

Workshop, 1-2 November 2017, Abu Dhabi, UAE

PROCEEDINGS

Table of contents


MISSION INNOVATION
Affordable Heating & Cooling for Building
Innovation Challenge Workshop
UAE, Abu Dhabi
1st, 2nd November 2017
MISSION INNOVATION

Foreword

These ***Workshop Proceedings*** report the technical findings of the Mission Innovation – Innovation Challenge #7 (IC#7) Workshop which was held in Abu Dhabi (UAE) on 1 -2 Nov 2017. The Workshop brought together 65 experts from 13 Mission Innovation Members and the Rocky Mountain Institute.

The Workshop first explored five *technological priority areas* and the main challenges and actions required for each of them:

- Thermal Energy Storage
- Heat Pumps
- Non-Atmospheric Heat Sinks and Sources
- Predictive Maintenance and Optimization
- Physiological Studies for Thermal Comfort

Following this activity the Workshop participants considered the priority area *Building level integration*. The experts identified and discussed a number of *cross-cutting issues* judged relevant for the IC#7 developments:

- Big and open data platform & build and operational standards
- Dynamic controls
- Non-air-conditioned buildings
- Heat system integration/ prosumer networks - Climate box
- Non-technological issues, such as user acceptance, bridging the gap between R&D and industry, skills and training

These ***Proceedings*** also include the workshop evaluation report, the preparatory technical documents which were completed for each priority area to steer the discussion of the technical session during the Workshop in Abu Dhabi and the list of participants.

The workshop participants are grateful to the **Ministry of Energy** of **United Arab Emirates** for having made this event possible.

Executive Summary

The discussion during the Abu Dhabi Workshop resulted in the identification of and agreement upon the main challenge, and areas of action to focus on for each priority area, reported below.

Thermal Energy Storage

The challenge

One of the biggest problems faced in low-carbon heating and cooling is the mismatch between supply and demand associated with the utilization of variable renewable sources. Thermal energy storage (TES) solves this problem and can be adapted in a variety of settings inside buildings and building components, and as part of wider networks grids.

Action areas

Develop ***more compact thermal energy storage*** for domestic applications of storage periods typically up to 4 weeks long. This will require materials that have virtually no heat losses but can take advantage of optimized solar and wind sources without district heating and cooling network connection.

Re-design ***large scale TES for district heating and cooling*** in order to match the seasonal supply and demand of a large number of renewable sources on a district level. This calls for new designs and novel materials to be used to achieve minimal surface area and double use of the top of the storage.

Develop ***compact thermal energy storage for electricity load shifting.*** These storage devices will take up electricity from the grid at the peak times in a day, to be used in the building for heating, cooling or hot tap water at later times. Typical charging power is in the order of 3 kW, for periods of up to three hours. The key development aspects here are: integration into the building heating system and in the smart electricity grid and then storage materials and technologies.

Heat Pumps

The challenge

This priority area covers potential research to accelerate the uptake of both electrically and thermally driven heat pumps by improving performance, reducing cost and achieving more effective integration.

Action areas

The main insight from the group was to think radically about heat pumps; no longer simply as a box on the wall but instead as a market enabler, merging energy vectors and delivering new services such as balancing.
Four key activities were identified that needed to be overcome:

1. Converting ***low grade heat to power*** (Target 60 °C heat to power at 10-20% efficiency)
2. Efficient ***gas to heat and cold*** (Target Gas Utilisation Efficiency of 1.6 (air source), 1.7 (water source) and 2.0 (in lab))
3. ***Integrated heating and cooling solutions*** (COP of 5.0 is currently achievable theoretically but better deployment needed to achieve this in practice)
4. Improved ***demand side management*** (targets are highly grid specific but aim to ensure security and stability of supply)

The workshop then focussed on the concept of a "Better-Box". This would be tailored to the specific application and geographic region but would take multiple energy sources as inputs and transform these into heating, cooling and power demands in the most optimal way (be that lowest carbon, lowest cost or lowest impact on the electricity grid). Internal components could include: electrically driven heat pump; thermally or gas driven heat pump; fuel cell; refrigeration; control system; and energy storage. The aspirational target for any "Better Box" would be to make it as cheap to buy, as easy to install and as cheap to run as the existing, most prevalent, high carbon alternative (e.g. gas boiler).

Non-atmospheric Heat Sinks/Sources

The Challenge

In hot climates, conventional air-cooled air conditioning system efficiency is penalized by the high ambient air temperatures and the same is true of heat pumps in low ambient temperatures. This priority looks to improve performance using the most promising technologies of evaporative cooling of chiller condenser, ground/sea/aquifer/wastewater sources/sinks interconnected via thermal network and low-wavelength radiation to deep space.

Action Areas

Develop ***indirect evaporative cooling*** of chiller by rejection of chiller waste heat against the wet bulb temperature of the building exhaust air. The basic principles are well understood but implementation and system integration challenges remain. Pilot projects should be conducted.

Improve system integration and precise balancing of ***district-wide thermal networks*** connecting non-atmospheric sinks and sources with thermal energy storage. This will involve extensive case-specific modelling and simulation to improve system design and operation. Establish the feasibility of adding active takers/providers of heat to address heating/cooling imbalance in the system.

Introduce ***low-wavelength radiation to deep space*** using a special high emissivity and high albedo film to enhance direct radiative loss from chiller condenser coils. This technology circumvents the atmosphere and directly transfers the heat to the cooler deep space. Detailed physical modelling and pilot projects are required as the material is still undergoing research and development.

In all cases, the emphasis will be on modelling, designing and testing generic solutions that can be easily adapted to specific conditions of participating countries. Metrics include lift reduction, COP improvement, life-cycle cost, life-cycle environmental impact, market penetration potential, present/future TRL (Technology Readiness Level), and generality versus regionality.

Predictive Maintenance & Control Optimization

The challenge

Poorly maintained, degraded, and improperly controlled HVAC equipment can waste up to 30% of the space conditioning energy used in buildings. Manual intervention from skilled practitioners can be highly cost effective but there is a general shortage of such skills. A variety of other barriers also exist such as split incentives and proprietary control systems. The challenge is to overcome these barriers by using emerging ICT technology and data science to automate this role.

Action areas

Develop a ***Knowledge Hub*** as a way of pooling the collective international knowledge on the topic and commission studies and surveys to supplement knowledge across different countries and climates. (Knowledge Hub website established and existing literature reviewed and published – June 2019 Longitudinal studies of split system/package-unit performance degradation completed – December 2021)

Develop ***Data Standards*** to reduce the level of investment required to benchmark buildings and compare performance to allow innovators to identify opportunities and develop solutions with wide applicability. (Frameworks, protocols and schema adopted for standardized collection of data – December 2019)

Establish an ***Open Data/ Building Emulator Platform*** to enable the development and testing of new solutions at much lower cost. (Cloud based, open-data/building emulator platform established – December 2019)

Enable and drive ***Innovation;*** while the actions above will encourage a myriad of new innovation opportunities to be explored, there is the potential to seed Grand Challenges to the innovator community to further accelerate activity. (Control and predictive maintenance algorithms

developed and validated; automated diagnosis demonstrated and maintenance strategies commercialized – December 2021).

Building-Level Integration and Cross Cutting Issues

The Challenge

Integrating different technologies together, either at the building level or district level was identified as one of the potentially greatest opportunities to improve the overall performance of heating and cooling systems. Following discussions in the workshop, five cross cutting areas were identified for further action.

Action Areas

Develop ***big and open data platform*** for build and operational standards – the Open Data Sharing Project. One of the largest problems in moving the HVAC industry forward is that performance data sets are owned primarily by private industry and trade organizations that do not make them publically available. As a result, there is very little comparable concrete data in the public domain to benchmark the performance of HVAC assets in the field versus in the lab. In the Gulf Cooperation Council (GCC) region it has been estimated that high end western style maintenance would be worth a 25% reduction in energy consumption and 50% reduction in HVAC carbon footprint. Project needs are:

- Gain government and industry support behind the concept
- Create a standardized data set
- Create a standardized way to share, store and analyse this data
- Analysis of the data by academic organizations

Use ***automation and dynamic controls*** to tap into the potential for low-cost demand response from building HVAC systems. Approaches include smart thermostats, ripple control of hot water storage or ice banks and behavioural approaches such as "cool biz" (Japan), and peak pricing incentives. Actions to unlock opportunities include:

- Develop more sophisticated control and engagement technologies to enable demand response, through the advent of Internet of Things, cloud computing, model predictive control and associated data sciences, including
    - Activate thermal storage
    - Widen comfort bands and utilise more sophisticated comfort sensors
    - Alternative pricing models, behavioural science nudge and peer-to-peer trading solutions
- Develop an autonomous solar cooling box that simultaneously takes both solar PV and air conditioning off the grid, while still managing comfort.

Develop solutions for ***non-air-conditioned buildings*** that do not use highly potent refrigerants and consume dramatically less energy, yet provide consumers with the cooling that they increasingly need. The energy demand and atmospheric impact of refrigerants under a business as usual scenario represents the single largest end use risk to meeting our climate goals. Two pathways were identified to pursue:

- A grand challenge or prize for the development and demonstration of extreme efficiency cooling solutions that can be implemented at market acceptable cost.
- Demonstrate mid-rise, low income, multi-family building prototypes incorporating market desirable features combined with low cost passive 'comfort' measures (i.e. balcony for shading, reflective surfaces) and easy incorporation of renewable energy and plug in future extreme efficiency cooling systems as developed under the first pathway.

Improve ***system integration / prosumer networks*** focused around taking forward the concept of a "Better Box" described under the "Heat Pump" priority area. The concept was renamed (working title) "the Comfort and Climate Box" and was further elaborated as an integrated heating and/or cooling unit to include the various elements developed under the separated priority areas. Such a "new" – decarbonized system:

- Needs to have adequate system output (in terms of heating and cooling).
- Should anticipate its impact on the overall energy systems in transition.
- Will form part of the solutions in a smart energy grid.
- Must enhance new business models for developing "heating and cooling services".
- Should achieve consumer acceptance.
- Should be deployable on a mass market basis.

The Technology Collaboration Programmes ECES and HPT were asked to develop the idea further in collaboration with other IEA-TCPs. It could be connected to several "super projects" to be developed as cross-cutting the borders of the various TCP's.

A number of ***non-technological issues*** need to be addressed in order to successfully make the transition from technology development to actual market implementation. Further work is required on these activities:

- End-user acceptance and end user use.
- Bridging the gap between R&D and industry.
- Opening up markets.
- Skills and training.

Physiological Studies

The Challenge

Application of various heating and cooling technology needs appropriate understanding about human comfort needs. These needs depend upon physiological, psychological and behavioral

conditions. Various climate and context need various approaches for cooling and heating. Methods to customize heating and cooling comfort technologies for design, installation and operation have been identified as a primary challenge.

Action Areas

Develop ***methods to understand human thermal comfort needs*** using advancement in Information Technology (IT). Based on knowledge generated, enhance HVAC systems capabilities to provide thermal comfort. HVAC systems should be capable of responding to changing human needs during time of day and seasons. IT technology should be able to facilitate HVAC operations based on adaptive thermal comfort model based on various climate contexts.

Develop ***metrics*** combining heating / cooling energy performance with thermal comfort performance. Such metric also should include human behavior and mode of building operations such as mixed mode building operation.

Develop ***data platform*** helping innovators and investors to take informed decisions; to disseminate information about capabilities of various technologies at concept stage to attract investment; by informing about performance gaps of HVAC systems, encourage innovators to apply their skills to meet challenges. Such platform also will be useful to map socio-behavioural implications of thermal comfort on building's energy use and may help new business model for HVAC services and products.

Develop ***HVAC / Sensors & Control technologies*** that understand short period human comfort requirements. Temporary comfort or understanding of thermal aesthesia should be explored to find solutions which can provide thermal comfort for short period of time; this could be applicable to transitional areas, or in the event of change in metabolic rate or change in immediate environment. Development of technology also can help reaching 'Rock Bottom' optimization during operation phase of buildings.

Workshop Results

Priority Area: Thermal Energy Storage

The need for Thermal Energy Storage (TES)

The energy supply from renewable sources varies both during the day and seasonally. The energy demand follows a variable profile both during the day and the seasons, as well. Thermal energy storage can help solve the specific challenge relating to low-carbon heating and cooling due to the mismatch between supply and demand and enables a higher utilization of variable renewable sources.

TES can be integrated in several ways and in several places in the heating and cooling system; either in a building or building component, in a heating and cooling system inside the building or integrated in a heating or cooling grid, exterior to the building.

In order for TES technologies to have a maximal effect on the innovation Challenge #7, three targets have been discussed and agreed upon as TES priority areas. In the following, these targets are described briefly, together with the targeted technology readiness levels (TRL) for 2020 and for 2030, for the complete technology as well as the main technology aspects. Note that the TRLs that can be achieved are highly dependent on the level of funding for the specific area.

Target A1: Intermediate period compact thermal energy storage (CTES) in buildings
A TES system that needs much less volume than state-of-the-art technologies is to be developed (typically 80 kWh/m^3 on system level for phase-change materials and 250 kWh/m^3 on system level for thermo-chemical material based systems), with materials that have virtually no heat losses and enable the storage of heat and cold for domestic applications for periods typically up to 4 weeks. With these stores, the use of varying solar and wind sources can be optimised in buildings without district heating and cooling network connection. Cost reduction is an important target, as the present solutions are still too expensive.

Table 1: Compact Thermal Energy Storage

	2018		**2020**	**2030**
Technology	**TRL**	**description**	**TRL**	**TRL**
Overall[1]	5-6		6	9
TCM	1	novel materials, e.g. ALPO, MOF	2	5
	3 - 4	composites	6	8
PCM	4-9		4-8	7-9
Heat exchanger/reactor	1 5-8	novel reactor designs adaptation of available heat exchangers[2]	3 8	6 9
Controls, modelling	1[3]-9	novel sensor principles for TCM and PCM	3-7	6-9

[1] rating applies to present, non-optimal technologies
[2] novel heat exchangers with required power output
[3] sensors for state-of-charge still have to be developed

Target A2: Large scale TES for district heating and cooling

District heating and cooling networks have to make the switch to be fully renewable, using a large number of sources. Seasonal matching of supply and demand can only be guaranteed with large scale thermal energy storages integrated in the network, mostly in an urban environment. An important additional function of the large scale TES is the ability to level out variations in the electricity grid by incorporating/connecting also heat pumps and CHP units. This calls for cost effective and new designs for underground storages, with minimal land area and functional use of the top of the storage, e.g. for a solar collector or a small city park. The very large volumes required, starting at 200 000 m^3, in combination with a design lifetime of 50 years call for the development of novel materials and designs. Different ways of combining renewable heating/cooling and electricity producing technologies should be investigated and demonstrated.

Table 2: Large scale TES				
	2018		**2020**	**2030**
Technology	**TRL**	**description**	**TRL**	**TRL**
Overall	3 - 6[4]	First demonstrators of smaller size on the market. Demonstration of different types of large scale TES, also interacting with interconnected heating/cooling/electricity grids.	5	9
Materials, components	1 - 4	Long lifetime: Polymer liners, integrated thermal storage materials, low cost vacuum insulation technology, lid construction	2 - 6	6 - 9
Stratifiers, Heat exchangers	5-7	Development with aid of computational fluid dynamics	7 - 9	9
Controls	5 - 7	In combination with DHC control and optimisation	7 - 9	9

Target A3: Compact thermal energy storage for electricity load shifting
These storage devices will reduce the demand for electricity from the grid at peak times during the day, allowing off peak electricity to be used in the building for heating, cooling or hot tap water at later times.

Table 3: Peak-shifting TES				
	2018		**2020**	**2030**
Technology	**TRL**	**description**	**TRL**	**TRL**
Overall	3 - 9	3: On basis of novel PCMs; 9: ice storage	5 – 9	9
PCM	3 - 9	Long lifetime: Polymer liners, integrated thermal storage materials, vacuum insulation technology	4 - 9	6 - 9
Heat exch; reactor; modelling	3 - 9	Development of subsequent generations with improved performance	5 - 9	9
Control; modelling	3 - 9		5 - 9	9

[4] TRL 6 for present large scale TES (with less than 200.000 m^3 volume)

Typical charging power is in the order of 3 kW, for periods of up to three hours. Integration into the building heating system and in the smart electricity grid is a key development aspect, next to the storage materials and technologies.

Enablers: a number of legislation changes can create market pull (taxes, energy performance directives and minimal required shares of renewable energy). Besides, novel business models and capacity building may enable earlier and stronger market uptake. With respect to TES in buildings, the costing should include capital cost of space in buildings, leading to a larger value of compact TES technologies.

Barriers to the development and market uptake are the existing gap between R&D and market, the lack of legal possibilities for grid operators to invest in storage, the lower consumer acceptance of large indoor appliances or installations, the long lifetime of the existing technology, the need for house retrofitting and the need for capacity building and the lack of industrial confidence to invest the required capital to produce new systems when the market is not yet there.

Indicators for the technology development targets are: the number of systems realised, the system efficiency and the specific heat storage costs. According to the application, the indicators on system level need further refinement. Besides these general indicators, other indicators can be used to measure the development of materials or components.

In the discussion the following MI Members showed interest in further developing the TES targets: EC, UK, DE, CA, NL, IN, DK, FI, IT, UAE

Priority Area: Heat Pumps

Summary

This priority area covers potential research to accelerate the uptake of both electrically and thermally driven heat pumps by improving performance, reducing cost and more effective integration. The key insight from the group was to think radically about heat pumps; no longer simply as a box on the wall but instead as a market enabler, merging energy vectors and delivering new services such as balancing.

Challenges

Four key challenges were identified that needed to be overcome:

5. *Converting low grade heat to power*. It was recognised that there were many sources of low grade waste heat from industrial processes, air-conditioning plant, and even mine water. A cost effective solution to convert this heat into electrical power would have multiple applications and could significantly enhance the efficiency and affordability of heating and cooling systems. Initial targets were set at converting 60°C heat to power at 10-20% efficiency, however it was recognised this activity would require more work to explore feasibility and set realistic yet achievable targets.
6. *Efficient gas to heat and cool.* While electrical heat pumps offered clear advantages in terms of coefficient of performance and theoretically very low carbon if fed with low carbon electricity, it was recognised that in many parts of the world the major difference in the price of gas and electricity meant that a gas driven heat pump working at lower coefficient of performance (COP) may be more cost effective, albeit with less impact on carbon emissions. Such technology presented lower barriers to entry than an electric heat pump and might form an interim step on the pathway to decarbonisation or indeed a key component if powered by hydrogen from low carbon sources. Based on expected Gas Utilisation Efficiency in 2020 of 1.4, targets were set for 2030 of achieving products on the market with a Gas Utilisation Efficiency of 1.6 (air source) and 1.7 (water source) and of 2.0 in laboratory conditions.
7. *Integrated heating and cooling solutions.* This challenge recognised that in many applications there is a demand for both heating and cooling in close proximity. A better integrated solution would be able to deliver a substantially higher COP than either the heating or cooling technology considered in isolation. COP of 5.0 is currently achievable theoretically but better deployment needed to achieve this in practice.
8. *Improved demand side management.* Seen as another area where there was significant opportunity to improve system level performance but targets were very difficult to set and highly grid specific. The aim should be not simply improved performance and cost reductions, but also to ensure security and stability of supply.

Having identified these challenges, the workshop focused more closely on challenge 3 and developing the concept of a “better-box” illustrated in Figure 1. Conceptually the “better box” for heating and cooling is equivalent to the Turing Machine for computing; taking multiple inputs of energy sources and using these and storage to meet heating, cooling and power demands in the most optimal way (be that lowest carbon, lowest cost or lowest impact on the electricity grid).

The three core components of this system being an energy transformer; a control system; and an energy storage system. The energy transformer is capable of converting and upgrading different energy vectors; for example gas to power, low grade heat to high grade heat etc. Different

components could be selected and integrated dependent on the precise functionality of the specific Better Box instantiation and could include; electrically driven heat pump, thermally or gas driven heat pump, fuel cell, refrigeration unit.

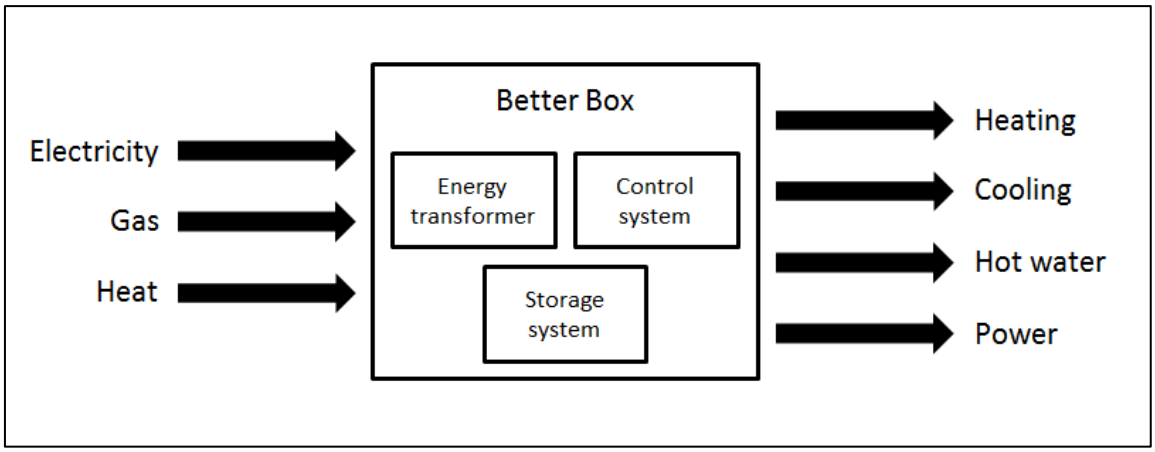


Figure 1: Better Box concept diagram

The workshop also considered what might be meant by "better". This was captured in the aspiration (rather than an achievable target) of being as cheap to buy, as easy to install and as cheap to run as the prevalent high carbon alternative in the area concerned (e.g. gas boiler).

Enablers

The following enablers were identified that might help bring the Better Box concept to market. No assessment was made of the feasibility of such changes occurring in practice:

- CO2 pricing / targets on low carbon system deployment
- Rating systems such as Eco-design labelling and Energy Star
- Incentives to retrofit the technology where buildings already exists
- Certification bodies for installers (but can be improved)
- Some consumers willing to pay more for improved climate e.g. cooling
- Software is available to perform much of the control functionality
- Exploiting other opportunities like demand side response

Barriers

Barriers were assessed similarly and included:

- Additional complexity – several major components in the box rather than a single well understood unit
- Very high costs without significant volume to reduce costs and volume unlikely without a reduction in costs
- The challenge of distributing low temperatures for cooling
- Consumer and industry conservatism
- Retrofit is a difficult market – people normally replace like for like
- Installation will require different skills and training and initially such a technology will be unfamiliar to most installers
- Technical feasible of creating such a product in practice
- New digital infrastructure in most countries needed to deliver demand side response

Breakout Participants
Jennie Dodson (UK); Marcello Aprile (IT); Graeme Maidment (UK); Jon Saltmarsh (UK); Robert Lowe (UK); Ammar Abdulateef (UAE); Michel Farah (UAE), Monica Axell (SWE); Korbinian Kramer (GE); Sophie Hosatte (CAN); Bob Critoph (UK); Neil Hewitt (UK); Dr Ali Al-Alili (UAE)

Priority Area: Non-atmospheric Heat Sinks/Sources for heat pumps

Abstract

This priority area covers all heat pump sinks and sources other than unprocessed ambient air. We propose to develop indirect evaporative cooling (IEC) of chiller by rejection of chiller waste heat against the wet bulb temperature of the building exhaust air. This technology is not widely used despite having high potential. Another major topic is district-wide thermal network connecting non-atmospheric sinks and sources with thermal energy storage. If heating and cooling do not occur simultaneously but are more or less balanced over a longer period, a thermal storage such as the ground can mediate the asynchronous transfer of heat—even across seasons. The aforementioned thermal network can be enhanced by the interconnection of active takers/providers of heat to address heating/cooling imbalance in the system. For instance, low temperature solar thermal or industrial waste heat resources can bring balance to a thermal network where heating loads exceed cooling loads. Alternatively, if the heat rejected by the network's chillers exceeds that needed by interconnected heat pumps, some of the extra heat can be extracted and used in low grade heating applications such as drying, solid/liquid desiccant regeneration (dehumidification systems) and pre-heating stage of other processes. The long-wavelength radiation to deep space is made possible by using a special high emissivity and high albedo film to enhance direct radiative loss from chiller condenser coils. This technology circumvents the atmosphere and directly transfers the heat to the cooler deep space. In all cases, the emphasis will be on modeling, designing and testing generic solutions that can be easily adapted to specific conditions of participating countries.

Scope

This priority proposes to promote heat pumps (heating/cooling) that do not use the ambient air as heat sink or source. As such the scope of the priority encompasses all heat pump sinks and sources other than unprocessed atmospheric air. The goal is to reduce the lift, thereby making the heat pump more efficient. The most promising technologies are indirect evaporative cooling of chiller condenser, ground/sea/aquifer/wastewater sources/sinks interconnected via thermal network and long-wavelength radiation to deep space.

Technologies and challenges

1) *Indirect evaporative cooling (IEC).* We propose to develop indirect evaporative cooling of chiller by rejection of chiller waste heat against the wet bulb temperature of the building exhaust air. This technology is not widely used despite having high potential. The basic principles are well understood but implementation and system integration challenges remain. Pilot projects should be conducted.

2) *Thermal network.* A district-wide thermal network can connect non-atmospheric sinks and sources with thermal energy storage. If heating and cooling do not occur simultaneously

but are more or less balanced over a longer period, a thermal storage such as the ground can mediate the asynchronous transfer of heat—even across seasons. The challenge here is system integration and precise balancing. System design and operation requires extensive case-specific modeling and simulation.

3) *Interconnection of active devices (a further enhancement of technology #3).* The thermal network can be enhanced by the interconnection of active takers/providers of heat to address heating/cooling imbalance in the system. For instance, low temperature solar thermal or industrial waste heat resources can bring balance to a thermal network where heating loads exceed cooling loads. Alternatively, if the heat rejected by the network's chillers exceeds that needed by interconnected heat pumps, some of the extra heat can be extracted and used in low grade heating applications such as drying, solid/liquid desiccant regeneration (dehumidification systems) and pre-heating stage of other processes. Here too, the challenge is mainly system integration and balancing. Feasibility must be established via numerical modeling for typical configurations.

4) *Deep space radiation cooling.* The long-wavelength radiation to deep space is made possible by using a special high emissivity and high albedo film to enhance direct radiative loss from chiller condenser coils. This technology circumvents the atmosphere and directly transfers the heat to the cooler deep space. The challenge here is mainly technological, since the material is still undergoing research and development. Implementation is straightforward although large sky-exposed area is required. Detailed physical modeling and pilot projects are required.

Research framework

In all cases, the emphasis will be on modeling, designing and testing generic solutions that can be easily adapted to specific conditions of participating countries.

The limitations of the proposed technologies include:

- The likely low temperature gradient (between source and sink) of the thermal network could lead to large infrastructure costs and high pumping energy
- The legacy (atmospheric) systems will end up being significantly over-sized after connection to the thermal network; the chillers may therefore have to operate mostly at part-load which often corresponds to mediocre efficiency
- An access cost must be levied for interconnection to the thermal network in order to make the technology bankable; the usual principal-agent problem applies
- The deep space radiation cooling technology is still in research stage and significant investment of time and capital is required before large-scale commercial deployment is possible

Performance Goals

Performance metrics include temperature lift reduction, COP improvement, life-cycle cost, life-cycle environmental impact, market penetration potential, present/future TRL (Technology Readiness Level), generality versus regionality.

Preliminary performance objectives, to be achieved at the completion of the proposed research activities, are summarized in the table below.

Table 1: Identified technologies for non-atmospheric heat sinks/sources

	IEC	***Deep Sky Radiation***	***Smart thermal network*** ***(building and district level)***
Life cycle cost	50% of baseline heat pump	System IRR comparable to baseline (dry cooling tower)	Cost of delivered energy: Less than conventional air-sourced heat pump powered by grid electricity (by 20-30%)
Temperature lift	-	15 degrees (requires modeling)	20 degrees
TRL	(dry to wet cooling) TRL-8/TRL-9	TRL-7	Waste heat recovery TRL-7 Ground TRL - 9
Regionality	Cooling tower for humid regions and direct sensible cooling for dry regions	Surface limitation Cloud coverage	-
Environment (carbon payback)	Sea water Wastewater (1 year)	(2 years)	In the heating case, use solar thermal to complement waste heat; renewable/waste heat fraction: 80%
Performance	Similar to open wet cooling tower	-	-

Barriers & Enablers

Barriers include:

- Heavy infrastructure requirement in the case of the thermal network

- The proposed thermal network is in competition with district energy
- Adds complexity for end-users
- Metering/billing of the thermal interconnection activities
- Business model and even infrastructure type are highly dependent on climate and use mix

Enablers include:

- The thermal network concept presents synergies with smart grid
- The mode of interaction between the thermal network and the connected devices is similar to the concept of grid-connected distributed energy generation (prosumer)
- All technologies contribute to the mitigation of the urban heat island
- End-users retain ultimate control of the electricity consuming equipment (heat pump)

Proposed research, development & demonstration projects

Unless specified otherwise, the following activities apply to all technologies:

- Acquisition of demand data for selected sites
- Modelling and feasibility analysis
- Optimal design of different configurations for different cities
- Life-cycle analysis
- Technology Development (deep space radiation cooling)
- Pilot Projects with focus on different climates and use mixes (IEC, deep space radiation cooling)
- Development of business model(s)

Priority Area: Predictive Maintenance & Control Optimization

Poorly maintained, degraded, and improperly controlled HVAC equipment can waste up to 30% of the space conditioning energy used in buildings.

Manual intervention from skilled practitioners can be used to identify these issues and implement corrective action to save energy. On average, this is highly cost effective, with payback times of less than 18 months. However the opportunity is rarely taken up.

Unfortunately, there is a general shortage of skilled practitioners. And the energy savings value that they could provide, in a given building, is unknown at the time of their appointment to the task (when the cost is incurred). This makes it difficult to mount an initial "business case". A variety of other barriers also exist including (i) split incentives for both tenants and facilities managers, and (ii) proprietary control systems that limit access to building data and services.

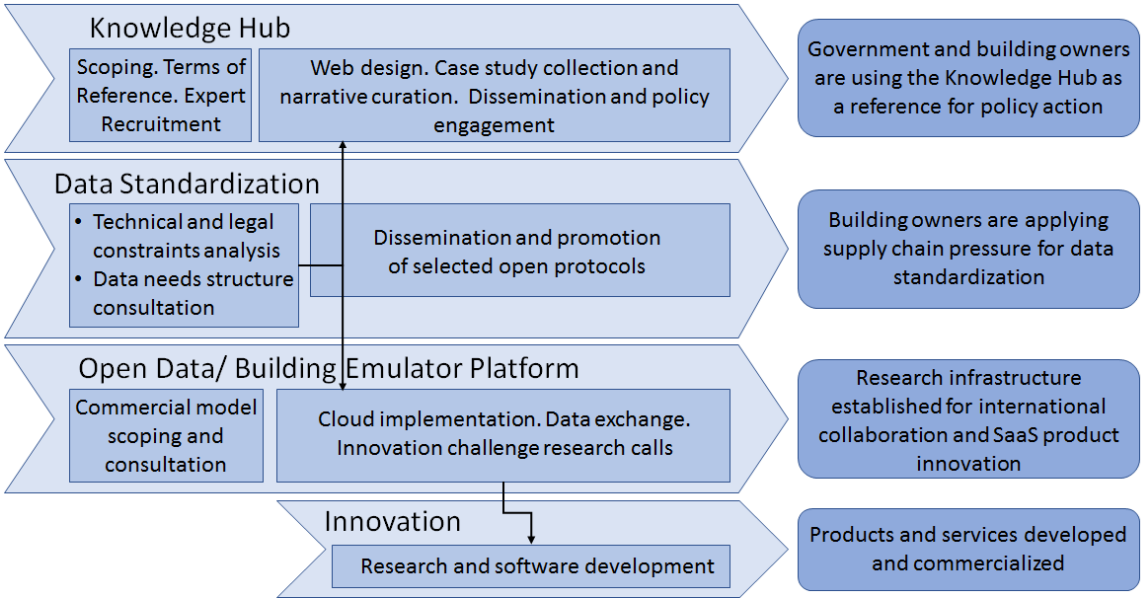
The challenge then is to overcome these barriers by using emerging ICT technology and data science to automate the knowledge of the skilled practitioner in a manner that is easy to use, and dynamically actionable through building control systems and processes.

The overarching target of the predictive maintenance and control optimization priority area is to reduce the energy consumption and CO_2 footprint of buildings by 30%. This will be achieved by the large scale adoption of automated predictive maintenance and building control optimization algorithms, including

- Dynamic controls (self diagnosis, self correction, self learning); and
- Intuitive, cloud-based, user engagement interfaces for maintenance staff and occupants

In addition to the development of advanced predictive maintenance and control optimization technologies, there is a need for supporting "trusted advisor" research to (i) independently validate performance and outcomes from real world implementations and (ii) make building data widely accessible to potential service providers.

Recommended research, and associated outcomes, are illustrated below



The *Knowledge Hub* is proposed as a way of pooling the collective international knowledge on the topic, through systematic reviews, and providing the evidence base for governments to pursue policy action. This is required because ultimately, regulation may be required to ensure the necessary scale of adoption. Additional longitudinal surveys of equipment health should also be commissioned to supplement knowledge (particularly of ubiquitous split systems and package units in different countries and climates).

Data Standardization and the *Open Data/ Building Emulator Platform* are enabling research activities that serve a number of purposes, including (i) benchmarking of buildings and (ii) developing new products and services. Significant work has already been done on data standardization (eg BACNet and Project Haystack) but more work is required to open up the market to innovators. Aspiring vendors of new applications must currently invest significant effort in getting access to sites, creating custom interfaces to equipment, decoding point labels, extracting data and converting into addressable data formats – all before they add any value to the data through any new application. This is in contrast to the broader IT industry, from cloud computing to mobile applications, where industry has created standard protocols, APIs and formats which enable start-ups to innovate and thrive in the larger ecosystem – with the end user being the beneficiary of this standardization in the form of improved functionality, increased performance and/or savings.

With the Open Data Platform providing a "sandpit" for research, and access to real buildings for early stage commercialization, a crowd-sourcing app-development approach can be used to drive *Innovation*. Potential exists for a myriad of innovation opportunities to be explored using *inter alia* data science, user engagement interfaces, and behavioral economics science. Noting that successful commercialization of new products will likely result from the bundling of a number of applications (energy, maintenance, security, lighting, occupant behaviour, etc.), it is not the intention to be prescriptive of the specific innovations being undertaken. Potential exists to seed Grand Challenges to the innovator community surrounding the Open Data Platform.

Research targets include

Research Target	Timing
Knowledge Hub website established and existing literature reviewed and published • Energy saving benefits of dynamic controls are independently validated with sufficient frequency and certainty, to convince policy makers to mandate it (i) in government buildings (2021), and (ii) nationally (2030)	June 2019
Legal framework, naming protocols, and communication protocols selected for curating and sharing data/information Schema adopted for standardized collection of building data to validate HVAC building performance in different building types/climates	December 2019
Cloud based, open-data/building emulator platform established	December 2019
Dynamic control and predictive maintenance algorithms developed and validated in living laboratories across different building types, HVAC technologies and climate zones; demonstrating • Maintenance staff prioritize their decisions, and apply the advice from	December 2021

diagnostic tools, because advice is presented via intuitive, easy to use, mobile-interfaces • 80% of maintenance issues are detected ahead of time with <20% false positives • Comfort related complaints are reduced by 50% through occupant engagement interfaces and self-diagnosing, self-correcting (fault tolerant) HVAC controls • Cost and complexity of implementing dynamic control technology is reduced by 50% by utilizing the open data platform as a commercial service	
Longitudinal studies of split system/package-unit performance degradation completed. Automated diagnosis demonstrated and maintenance strategies commercialized	December 2021

MI Member Countries committed to pursuing research in this priority area include Australia, Canada, France, India, Netherlands, UAE, UK (which still need to confirm their interest).

Priority Area: Building level integration

Summary

This priority area covers potential research to integrate heating and cooling solutions into buildings and districts to provide the most effective overall system. Successfully matching the design of the building to the performance of the heating and cooling solutions will have a large impact on the overall efficiency of the system. The priority area was discussed in all the groups but it was not treated as a separate theme in the initial group discussion. From a building perspective it is of course most important to start with reducing the energy demand. Furthermore building integration and district integration can contribute to improved overall system efficiency and large energy savings.

Challenges

Six key challenges were identified that needed to be overcome:

1. *Open data platform*. Digitalisation is an enabler of improved performance, but the lack of an open data platform and common operational standards is probably one of the largest barriers for improved integration, predictive maintenance and performance optimisation at a building or district level. For example potential to energy savings with predictive maintenance is as large as 30%.
2. *"Heat pump ready buildings"= Small temperature lift for heating and cooling.* New innovative affordable solutions for heating and cooling are needed and the overall system efficiency will be influenced of the design of the building. No heat pump cycle can have efficiency above the Carnot limit which is dependent on the temperature lift. Heat pump cycles will increase their efficiency with low temperature distribution system for heating and high temperature distribution system for cooling. Furthermore an increased knowledge about thermal comfort and the safety needs driving domestic hot water temperature requirements can contribute to decrease the temperature lifts.
3. *Simultaneously heating and cooling.* At a building and/or district level it is common to find simultaneous demands for heating and cooling. If this can be produced with the same system, there is a huge potential to improve efficiency and save energy. Added benefits include reducing heat island effects and less noise disturbance.
4. *Improved demand side management.* Opportunities to take advantage of the thermal mass of the building and the equipment in the building, as a means to reduce peak loads, are not taken often enough. There is a need for more knowledge about dynamic control and thermal comfort of end users to increase the potential to use the building itself as a storage medium.
5. *District integration*. The challenge today is that waste heat like heat from condensers (AC), greywater from buildings, from industrial and other processes in the buildings, from other sources in the city (metro, data centers, etc) are not fully utilized. There is a large potential to save energy, improve efficiency and work with demand side management by having a district integration approach. One of the conclusions from the discussions was a need for new business models and policy to take advantage of the fact that one organization's waste heat is another's resource. Furthermore the upfront cost for building new district infrastructure needs to be overcome.
6. *Cooling demand in warm and humid climates*. The issue here is that cooling demand will grow rapidly in warm and humid climates. Several challenges were identified: lack of

new refrigerants; need to build installation capacity and a need for affordable alternative technologies like non air conditioned buildings. In addition focus on standardization and energy performance labelling schemes will be of importance.

Having identified these challenges, the different cross cutting groups discussed them in more detail. A general conclusion was that it would probably be very beneficial to undertake a thorough segmentation of buildings including their types, uses and locations. This would allow focus on a few specific applications to speed up the innovation process. Possible initial application discussed were hospitals, offices, supermarkets, hotels and multi-family buildings. The aim being to accelerate the journey *"from data to wisdom"*. In addition the need for KPIs was discussed and in particular the need for increased knowledge about the impact of affordable heating and cooling on GDP, long term health effect and CO2 savings.

Enablers

The following enablers were identified that might help bring new technology, systems and concepts to market.

- CO2 pricing / targets on low carbon system deployment
- Rating systems on building level performance exist but can be improved.
- Rating systems on district level performance need to be developed
- Incentives to retrofit buildings which favour a whole building integrated approach.
- Tools for building and district level integration
- Capacity building - building and district level integration
- Certification bodies for installers and other key actors in the value chain.
- Some consumers willing to pay more for improved climate and comfort
- Exploiting other opportunities like demand side response
- End users will have a large impact on the future - need for improved knowledge and facts
- Mapping of waste heat potential at a building and district level exist, but need to be further explored
- Digitalisation, to explore possible cross cutting activities with other sectors
- Energy savings and energy efficiency will improve outdoor climate in cities.

Barriers

Barriers to overcome were discussed:

- Open data platforms
- High up-front costs can be a barrier for system integration. There is a need to decrease up front cost and to increase the acceptance of life cycle cost.
- New key actors need to find ways to make business together
- Retrofit is a difficult market. From an energy and system integration perspective it would be beneficial to make retrofit on several systems, components at the same time.
- Building sector is fragmented. Building and district integration will require different skills and training - Capacity building
- End use behaviour can be a barrier for acceptance of new technology, systems and concepts.

Priority Area: Physiological studies for thermal comfort

Participants

1) Rajan Rawal, CEPT University, India - rajanrawal@cept.ac.in
2) Paul Jordan, CATAPULT Energy Systems, UK - paul.jordan@es.catapult.org.uk
3) Marco Simonetti, Polytechnic of Torino, Italy - marco.simonetti@polito.it
4) Paul Cooper, University of Wollongong, Australia - pcooper@uow.edu.au

Developing priority area targets

Advancement in understanding human thermal comfort can be carried out by studying three interdependent yet distinct study areas, namely (a) Physiological studies (b) Psychological studies and (c) Behavioural studies. Psychology and behaviour have significant impact on human thermal comfort. Earlier it was proposed to focus, within the framework of Mission Innovation, on human physiology and its relationship with thermal comfort. This was proposed envisaging advancement in technology needed to achieve energy efficiency in heating and cooling. Group discussed the title of the priority area, and propose to expand its scope to area of thermal comfort.

With two overarching measurable goals namely (a) Access to thermal comfort to citizens of Mission Innovation (MI) member countries (b) Specify wider and contextual thermal comfort range based on adaptive thermal comfort theory, the following targets were identified.

1. Connecting thermal comfort with Information technology.
2. Access impact of technologies in providing comfort and achieve energy efficiency. Identify technologies which can provide comfort as per adaptive thermal comfort theory.
3. Develop common platform for low energy heating and cooling design and technology data
4. Identify technological opportunities to provide thermal comfort for short period of time. Take opportunities to explore concept of thermal allethesia.

The following narrative elaborate on the four targets.

1. **Connecting thermal comfort with Information technology.**
   a. Develop affordable sensing technologies to gather higher number of data points to understand thermal comfort in various cultural and climate context.
   b. Develop affordable sensing technologies to control low energy comfort technologies. Enhance ‘smartness’ of low energy comfort technologies.

Enablers and Blockers: (a) Barriers in sensing technology, economics of it, integration of it. (b) Proprietary versus open platform, communication with HVAC hardware.

Number of innovation leading to product in sensing and controlling heating and cooling systems in affordable and scalable manner will be one of the ways to determine progress.

2. **Access impact of technologies in providing comfort and achieve energy efficiency**. Identify technologies which can provide comfort as per adaptive thermal comfort theory.
    a. Link energy performance of comfort technologies with their ability to provide comfort in various climate contexts.
    b. Increase aesthetics of air motion devices, evaporative cooling technologies and heating technologies to suite contemporary interiors. Encourage mixed – mode building operations.

    Enablers and Blockers: It will be challenging to decide common denominator against which energy and comfort benefit of technology can be evaluated. Evaluation at laboratory level and in field will deliver different performance numbers.

    Increase number in mixed mode operation buildings could be one of the metrics against which success of this can be determined. Amount of energy saved and level of thermal comfort provided by building to occupant could be another metrics.

3. **Develop common platform for low energy heating and cooling design and technology data**.
    a. A single platform which can enable innovators and investors to take informed decisions. A common platform which can provide insights into physiological, psychological and behavioural needs of building occupants.
    b. Develop modelling technologies capable of estimating user need for thermal comfort, guide towards building operation and envisage need for thermal comfort.

    Enablers and Blockers: MI secretariat needs to identify an organization that can design data collection framework and gather volunteers.

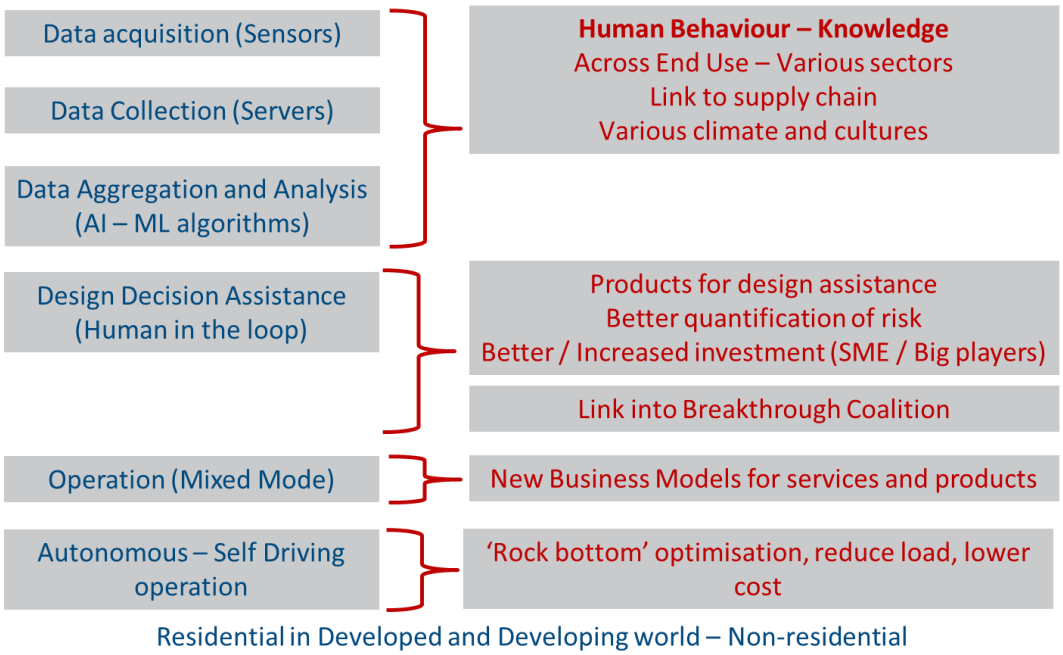
    Number of trialists and number of innovators using common data platform to develop commercially viable products be one evaluation point. Second could be amount of investment made using data platform in to research.

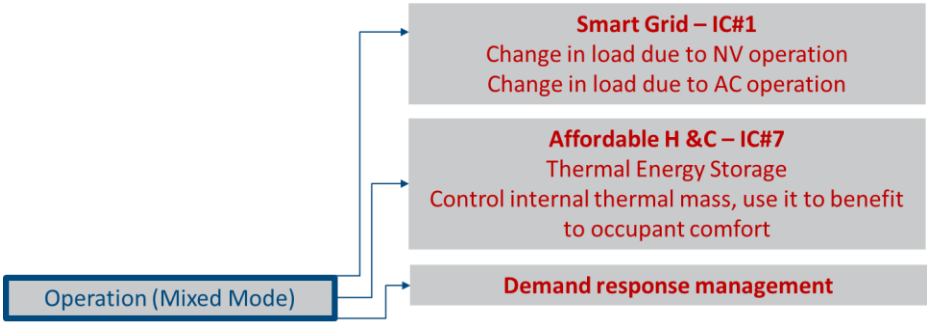
4. **Identify technological opportunities to provide thermal comfort for short period of time**. Take opportunities to explore concept of thermal allesthesia.

a. Develop tools and technology which can take advantage of thermal allesthesia. Target transit spaces and / or extreme climate context.

Enablers and Blockers: It will be challenging to account for cultural and climate context while identifying effectiveness of technologies.

Number of design interventions and number of technologies developed to enhance personal thermal comfort could be one of the metrics.





Cross Cutting Themes for Integrating Technologies in the Buildings

Integrating different technologies together, either at the building level or district level was identified as one of the potentially greatest opportunities to improve the overall performance of heating and cooling systems. Following discussions in the workshop, five cross cutting areas were identified for further action.

Cross-Cutting Theme: Develop *big and open data platform* and operational standards

Open Data Sharing Project

One of the largest problems in moving the HVAC industry forward is that performance data sets are owned primarily by private industry and trade organizations that do not make them publically available. As a result, there is very little comparable concrete data in the public domain to benchmark the performance of HVAC assets in the field versus in the lab. In the Gulf Cooperation Council (GCC) region it has been estimated that high end western style maintenance would be worth a 25% reduction in energy consumption and 50% reduction in HVAC carbon footprint. Project needs are:

- Gain government and industry support behind the concept
- Create a standardized data set
- Create a standardized way to share, store and analyse this data
- Analysis of the data by academic organizations

Points of discussion

In our pursuit to study the human body we standardized the critical data points and have been benchmarking those data points for over a century now. In the care of HVAC-R assets we have not standardized or ranked the most critical measurable points of information for the care of HVAC. With the human body we identified how to measure, where to measure and how to report: Heart-rate, Blood-pressure, Pulse-Ox, Temperature and Respiratory-rate; as the preliminary baseline measurement points for all human healthcare analysis; these data points then drive further specialized prioritized measurements based on the first round of these critical stats. This type of decision tree analysis is not recorded for this HVAC data, but it is routinely performed by technicians in the field. Unfortunately, the vast majority of this data is not captured in a permanent manner that can be analyzed easily and as a result, very little information from the field is gathered to create clear data sets for study.

Solution

1. We need to create a standardized data set

2. We need to create a standardized way to share, store and analyze this data.

3. We need to get government and industry support behind this idea.

4. We need to get academic organizations to start analyzing the data

Suggested critical data set

I.E.Q: Inside CO2 levels (this variable has been studied to be worth 3.5% of GDP)

Maintenance: Refrigerant leak-rate, Graded Coil cleanliness rating, Graded Oil analysis, Graded Chilled water analysis, Inlet temp/pressure, Outlet temp/pressure, Reported Coefficient of Performance, & Delta T internal/external (Lift analysis)

Comfort: Inside temperature, inside humidity, & Recorded annual downtime

Why would this problem still exist in 2017?

1. Many leading companies in the industry have closed garden monitoring systems that are designed for their own equipment.

2. Often there are misaligned stakeholder interest (the guy who maintains the equipment is reverse incentivized to report the exact details of the caliber of the work they are doing, or worse, there is financial gain when the equipment fails.

3. Communication of this information is primarily captured on paper, if captured, and very little makes it to an integrated electronic platform.

4. Only one-third to half of the data can be economically captured using sensors, (a smooth way to collect data from technicians is required)

5. Most business owners and building owners can't afford a dedicated team member for HVAC-R performance analysis

Who is affected by this problem?

1. Governments have to spend 20% to 30% more on energy infrastructure and healthcare, while simultaneously losing a competitive edge to cities that run more efficiently.

2. Asset owner that pays for the energy and is concerned with downtime for their brand is the person that is closest and most affected by the financial implications of better care for their most expensive assets (beyond the shell of their buildings).

3. Asset owners that rent the property to other tenants and may not pay utilities are less concerned

4. Tenants are profoundly affected by energy bills, equipment failures and air-quality but have the least leverage to affect the care of the equipment

5. Maintenance companies that perform at a high level may be positively impacted while other maintenance companies that perform poorly may be negatively impacted if they are making their margin based on a lack of visibility into their work

6. HVAC-R asset manufacturers will be affected in a similar way to the maintenance companies, both the high and low performers will be recognized.

Cross-Cutting Theme: Dynamic Controls and Grid Integration

It is widely acknowledged that demand side participation in electricity systems should increase competition and improve market efficiency, leading to lower electricity prices. Building heating and cooling offers many low cost opportunities for demand side participation. For example, the inherent thermal storage available in building thermal mass represents a "free" storage resource for both reducing electricity industry peak demand, and managing the intermittency of variable renewable energy sources.

Countries have diverse electricity industry structures and constraints, which make demand side participation from building HVAC systems either more, or less, mature. In most cases there are substantial transaction costs involved in recruiting and enabling buildings to perform as demand response resources.

The key opportunity for accessing these untapped low-cost demand response resources and reducing transaction costs is through automation and the development of dynamic controls, in so called Smart Buildings. Example dynamic control technologies in heating and cooling applications include smart thermostats and ripple control of hot water storage or ice banks. Behavioural approaches such as "cool biz" (Japan), and peak pricing incentives have also been adopted in some jurisdictions. Incentive and clear framework for self-consumption of solar PV output to allow self-consumers to generate, store, sell and consume their own electricity can also drive changes to building electricity demand profiles.

Cross cutting research to unlock opportunities include:

- Develop more sophisticated control and engagement technologies to enable demand response, through the advent of internet of things (IoT), cloud computing, model predictive control and associated data sciences (links to Priority Area D), including
    - Activate thermal storage (links to Priority Area A)
    - Widen comfort bands and utilise more sophisticated comfort sensors (links to Priority Area F)
    - Alternative pricing models, behavioural science nudge and peer-to-peer trading solutions (links to Priority Area D)
- Develop low cost, compact thermal storage (links to Priority Area A) both for short term (low latitude locations) and seasonal storage (high latitude locations) applications.
- Develop an autonomous solar cooling box that simultaneously takes both solar PV and air conditioning off the grid, while still managing comfort (links to Priority Area B and F).
- Integrate large scale controllable thermal storage into district level cooling to provide peak demand management (Links to Priority Area C).

Cross Cutting Theme: Non Air-conditioned buildings

As population, urbanization and incomes continue to accelerate within the context of a warming planet we will see increasing rates of adoption of mechanical cooling systems with the greatest penetration occurring in developing nations in hot and humid climates. The business as usual scale of this adoption would result in 1.6 billion air conditioning units being deployed between now and 2050 requiring thousands of new power plants to generate the 6,000 TWh of electricity needed to power these and the approximately 0.9 billion air conditioning units already deployed. Combined with the atmospheric impact of the refrigerants utilized by these systems, this likely represents the single largest end use risk to meeting our climate goals.

The growing demand for mechanical cooling systems will come from non-air-conditioned buildings. The development of solutions that do not use highly potent refrigerants and consume dramatically less energy can provide consumers with the cooling that they increasingly need, decrease pressure on already strained grids while helping to address this looming climate crisis.

The working team in this area sought to narrow the focus further to ensure that recommendations would be actionable and determined that the focus should be on residential buildings in dense urban environments in hot and humid climates. These solutions needed to encompass comfort, low cost, low energy with minimal generation of waste heat to atmosphere and noise pollution. Two pathways to impact were identified with a focus on India for demonstration based on future business as usual demand.

The first of these was application to existing buildings through a grand challenge or prize for the development and demonstration of extreme efficiency cooling solutions that can be implemented at market acceptable cost. Solutions are likely a combination of packaged systems incorporating fans, ventilation, dehumidification and small capacity active cooling.

The second of these was application to new construction through the demonstration of mid-rise low income multi-family building prototypes (in collaboration with industry) to inform the market and future code incorporating market desirable features combined with low cost passive ‘comfort’ measures (i.e. balcony for shading, reflective surfaces) and easy incorporation of renewable energy and plug in future extreme efficiency cooling systems as developed under the first pathway.

Cross-cutting Theme: Heat system integration /*prosumer* networks

Comfort and Climate box

Introduction

The concept is an integrated heating and/or cooling unit which will include the various elements developed under the separated PA's. The concept is called*: the Comfort and Climate Box (work tittle- further abbreviated as CCB).*

Such a "new" – decarbonized system need to have adequate system output (in terms of heating and cooling), but should also anticipate on the impact these systems will have on the overall energy systems in transition and will be part of the solutions in a smart energy grid. It will enhance new business models for developing "heating and cooling services". At the same time consumer acceptance is key for a fast and robust market introduction. The proposed systems will be deployed on a mass market to allow for a swift transformation of the heating and cooling markets to non-carbonized options. Deployment in larger districts needs to be developed further. Work on standardisation is essential to create a level playing field for suppliers of these systems and to reduce pricing. Systems need to be modular. New models are required, based on segmentation of markets, applications and regions (climate). With a collaborative approach within the context of Mission Innovation it is expected that first generation systems in large scale demonstrations can be introduced into the market in 2021. Newer generations are to be developed and introduced in period until 2030.

International collaboration

The IEA TCP network is an excellent infrastructure to accelerate the development of the concept. TCP ECES and HPT were asked to develop the idea further in collaboration with other IEA-TCP's. It could be connected to several "super projects" to be developed as cross-cutting the boarders of the various TCP's.

Breakthrough Energy Coalition

Support from the Breakthrough Energy Coalition need to be explored further. An exciting goal would be to have this CCB approach in MI#7 as a prime example on how to accelerate innovation through cross cutting collaboration between countries in close collaboration with the Coalition.

The new innovative system needs to

- Allow for easy installation- Plug and play
- Address mass markets to allow economies of scale / more economic
- Offer the opportunity to have one responsible supplier / installer to enhance consumer acceptance
- Anticipate on a strong marketing concept
- Lay the basis for new business models
- Contributes to flexibility in E-system
- Be based on energy savings and renewables
- Decreases pollution
- Allow for a consistent and effective capacity building

Targets for the concept

- Cost reduction xx %
- Increase Energy efficiency xx %
- Improved flexibility xx kWh
- Compact in size
- Increased use of RES

Description of desired functionalities

- Provide Heating and/or Cooling
- Includes (compact) Thermal Energy Storage (TES)
- Allow for PV feed
- Allow for Solar Thermal feed
- Integral control function, anticipating on grid- and supply conditions

Optional functionalities

- Provide for hot water
- Connectivity to waste heat and/or low temp heat/ cold grids
- Ventilation / heat recovery
- Electrical storage
- District options (a “nest” of systems)

Control functions

- Anticipating on weather prediction
- PV output and contribution
- Dynamic energy pricing
- Solar thermal output and contribution
- Variable output to match load profiles
- District options

Cross cutting Theme: Non-technological issues

There are a number of non-technological issues that need to be addressed in order to successfully make the transition from technology development to actual market implementation

The first issue concerns end-user acceptance and end user utilization. Ultimately, the end-user would like to have thermal comfort, provided by technologies that are accepted or even embraced. However, reliability, pricing, transparency of the value chain, data protection and clear quality standards are important elements in the end-user acceptance.

The second issue requires to bridging the gap between R&D and industry. This can be done by informing industry and investors on innovation challenges, by presenting opportunities and identifying gaps and getting their feedback on investment, business models, market structure, route to market, regulation/subsidies/incentives and on policies to open up markets and to enable or stimulate R&D.

The third issue which has been identified is opening up markets, by standardisation, implementing minimum renewable energy levels, finding appealing first customers and field tests. A further instrument is regulation or legislation that helps the architecture and governance of the future energy system. Knowledge sharing will help to open up market, for instance by using open platforms in the development.

The fourth issue concerns skills and training. The novel technologies and business models generate the need for new or different kind of skills and talents. The knowledge to obtain these skills should be provided to the educational sector and policy makers should be informed to create awareness of future shortage in specific skills.

Workshop Evaluation Report

Summary: Overall, the feedback praised an excellent, well run, highly beneficial event with participants[5] looking forward to continuing these activities, sharing information and moving forward, transitioning to greater private sector engagement and hopefully starting collaborative projects next year. There was a suggestion that such workshops, to find new solutions with people working on the same issues but from a different background, could also be carried out remotely (e.g. through webinars, or working on online documents together). There were various suggestions for additional topics to cover.

Workshop most and least useful element

When asked what was most useful, participants particularly noted the break-out discussion, experts involved, contacts made and the discussion on respective country situations and priorities. Iain Campbell's input was also noted as inspiring. When asked about the least useful aspect a few participants mentioned the cross-cutting session, although they regarded this as important, so it appears to be more how the session worked. More time or specific sessions for networking, and possible sessions with other PAs to get a broader flavour of their activities rather than from the feedback sessions, were suggested.

New international contacts/collaborations

All participants confirmed they will be in contact with new contacts; several already have done so either by "LinkedIn" or arranging to meet at a future event. One participant is also trying to connect people who couldn't attend with those who could be useful contacts. All participants envisage or would consider new international collaborations - with two already taking actions in this area (one under IEA collaboration). One was unsure how this would be funded, and another stressed the importance of having an international collaborative framework for MI, or to leverage

[5] Reference to participants means those who participated and responded to the evaluation survey which were 20 (out of 65 participants)

the IEA one, as proposed. Several participants mentioned collaboration with IEA, although with one voiced concern that whilst there was a role for the IEA to promote information exchange within the MI community it should not actually lead the agenda.

Workshop process and facilitation

Generally the feedback on the running and facilitation of the workshops was very good, with a variety of suggestions on how they could have been improved. These included prior briefing, with more instruction on how to prepare for the tasks and clearer deliverables/expectations for each discussion session, along with the use of a template from the start, a shared google doc for sharing notes, and a PowerPoint reporting template to facilitate the feedback sessions. Facilitation was praised, and seen as important given that it is easy to get drawn into discussions rather than reach conclusions.

Logistics and administrative arrangements

Feedback was very positive on logistics and administrative arrangements, with only one comment, that more time between confirmation of event date and the event would have facilitated agreement for travel and time to make arrangements. Several attendees suggested a dedicated workshop dinner, rather than the conference dinner, would have helped networking and facilitated discussion.

Additional topics

Suggestions on other topics that participants would like to have seen covered include:

- the system point of view could be more visible in the challenge
- electric heat pumps
- reducing loads – building envelope
- integration with buildings, heat networks, electricity networks and towns/communities

Miscellaneous

An additional point raised was to review the Priority Area titles, e.g. the thermal comfort topic – which referenced Physiological issues in the title previously suggesting this should be changed to either: Thermal Comfort and Energy (preferred) or Thermal Comfort.

The desire to build on the workshop was expressed as follows:

- Look forward to the path forward and transitioning to greater private sector engagement.
- Let's make sure that we keep the momentum built up in the workshop, e.g. by starting 2 or 3 collaborative projects by mid/end 2018.

Annex I: Workshop Programme

UNITED ARAB EMIRATES
MINISTRY OF ENERGY

MISSION INNOVATION
Accelerating the Clean Energy Revolution
www.mission-innovation.net

Affordable Heating & Cooling for Building Innovation Challenge Workshop

Day 1: Affordable Heating and Cooling of Buildings Innovation Challenge (IC#7)

Wednesday, November 1, 2017
Jumeirah at Etihad Towers, West Corniche, Abu Dhabi UAE.

Time	Details
9:30 – 10:00	**Coffee and registration**
10.00 - 10.30 **Session 1**	**Welcome to the workshop and to Mission Innovation** **H.E. Eng. Fatima Al Foora** -*Assistant Undersecretary for Electricity & Future Affairs, Ministry of Energy, UAE.* **Pietro Menna** -*Policy Officer, European Commission.* **Jon Saltmarsh** –*Head of Built Environment Technology, Department for Business, Energy and Industrial Strategy, UK*
10:15 – 11:00 **Session 2**	**Setting the scene: the challenge of Affordable Heating & Cooling** *Iain Campbell, Rocky Mountain Institute*
11:00– 12:00 **Session 3**	**The Innovation Challenge Priority Areas** **Background to the Priority Areas** *Pietro Menna* **A: Thermal Energy Storage** *Piero De Bonis, EC* **B: Heat pumps** *Jon Saltmarsh, UK* **C: Non-Atmospheric heat sinks and sources** *Dr. Afshin Afshari, UAE* **D: Predictive maintenance and optimization** *Stephen White, Australia* **F: Physiological studies for thermal comfort** *Rajan Rawal, India*
12:00- 13:00	Lunch
13:00- 13.15 **Session 4**	**Introduction to the parallel breakout sessions** *Rajan Rawal and Jennie Dodson*
13:15– 14:45 **Session 4**	**Developing Priority Area targets** Breakout sessions for priority areas A, B, C, D and F will be held concurrently Objective: The focus of this session will be to: • Identify 2-3 clear and concrete targets for each priority area: what needs to be achieved by 2030 in this priority area to accelerate the delivery of **affordable** and **low carbon** heating & cooling • Identify the enablers and blockers to achieving these targets • Identify metrics that could be used to track this target

14:45 – 15:15	**Coffee break**
15:15 – 17:00 **Session 4**	Continue to develop priority area targets.
17:00 – 18:30 **Session 5**	**Pitching targets** Each priority area will share the targets they have developed and there will be an opportunity to discuss, prioritise and share ideas across all priority areas.
19:00 – 21:00	Dinner with SHC conference attendees *(Ticket can be purchased on SHC website)*

Day 2: Affordable Heating and Cooling of Buildings Innovation Challenge (IC#7)

Thursday, November 2, 2017
Jumeirah at Etihad Towers, West Corniche, Abu Dhabi UAE.

09:00 – 09:20 **Session 6**	**Welcome, review of Day 1 and Overview of agenda for Day 2.** *Iain Campbell, Rajan Rawal and Jennie Dodson*
09:20 – 10:50 **Session 6**	**Mission Innovation Activities** Breakout sessions for priority areas A, B, C, D and F will be held concurrently Objective: By the end of this session each breakout group will aim to have: • Discussed and prioritised the most impactful activities that Mission Innovation could undertake to help achieve these targets, including identifying possible collaborations and interactions with other PAs. • If there is time, discuss what next steps are needed to achieve these targets i.e milestones for the next year.
10:50 – 11:10	**Coffee Break**
11:10 – 12.45 **Session 7**	**Feedback from PAs and Identifying Cross-Cutting / Building-Level Integration Issues** All PAs will share the outcomes of their discussion and specific ideas and actions to take forward. The whole workshop will then identify cross-cutting issues to discuss in the afternoon.
12:45- 13:30pm	**Lunch Break and Networking**
13:30 – 15:30 **Session 8**	**Building-level Integration and Other Cross-Cutting Areas** Building-level integration and cross-cutting topics will be discussed in small groups to identify targets and discuss further activities that MI could focus on.
15:30 – 15:50	**Coffee Break**
15:50 – 17:00 **Session 8**	**Feedback from Cross-Cutting Discussions**
17:00 – 18:00 **Session 9**	**Reflections and Workshop Close**

Annex II: Preparatory Technical Documents

Priority Area A: Thermal Energy Storage

Draft Technical paper for workshop preparation Abu Dhabi, 1-2 Nov 2017

The objective of the Affordable Heating and Cooling of Buildings Innovation Challenge is to make low-carbon heating and cooling affordable for everyone. This will be achieved by developing systems and measures to provide affordable solutions for the decarbonisation of the H/C sector through encouraging increased and better targeted investment by public and private sectors investors and through the promotion of increased collaboration among the Innovation Challenge Members and public and private sector investors.

1. Introduction

A particular challenge relating to low-carbon heating and cooling is the mismatch between supply and demand. Significant daily and seasonal variations in heating and cooling demand are compounded by daily and seasonal variations in the supply of energy from renewable sources. This results in a need for intra-day and, in some regions, inter-seasonal energy storage.

Thermal energy storage (TES) can be integrated in several ways and in several places in the heating and cooling system; either in a building or building component, in a heating and cooling system inside the building or integrated in a heating or cooling grid, exterior to the building.

A possible classification of TES into different applications is the following;

Table I: Break down of thermal energy storage activities

A	Heating of buildings - short term TES
	A1: TES in building elements A2: TES in heating system
B	Heating of buildings - seasonal TES
	B1: TES in heating system
C	Cooling of buildings
	C: Cooling of buildings
D	Improvement of (thermal and electric) grid flexibility
	D1: TES in the building or near the building D2: TES far away from the building

Every application has its own set of design requirements and performance indicators. A TES development program towards affordable heating and cooling in buildings can best be split down to parallel development tracks for the different applications. In each track, a certain number of technologies for TES will be developed in parallel.

2. Status of research

2.1 Mapping of the activities among Members

A survey was conducted into the TES activities for buildings/built environment among those MI Members that participate in the IC#7. 10 Members responded and in total 60 different project or programmes were identified, with the following breakdown in the TES applications:

Table II: TES activities by IC#7 Members resulting from survey

Country	A1	A2	B1	C	D1	D2	Total
Australia	0	3	0	0	0	1	**4**
Canada	0	3	0	0	0	1	**4**
Germany	1	8	1	1	1	0	**12**
UAE	0	0	0	3	0	0	**0**
EC	0	1	6	0	1	0	**8**
Netherlands	0	1	2	1	1	1	**6**
Norway	0	1	0	0	0	0	**1**
UK	0	8	0	0	1	0	**9**
China	0	0	0	0	0	1	**1**
Sweden	0	4	0	1	0	5	**10**
Denmark	0	0	0	0	0	2	**2**
Total	**1**	**29**	**9**	**6**	**4**	**11**	**60**

It is worth to note that most projects are in the application A2 (short term TES in building heating system) with 29 projects by 8 active Members, followed by D2 (TES for improvement of grid flexibility in grid system) with 11 projects by 6 active Members and B1 (seasonal TES in heating system) with 9 projects by only 3 active Members. The projects include activities concerning both the service of the loads and reduction of the energy demand through the use of building mass and integration of PCM TES systems within building elements.

2.2 Technology development per application

A1 (Short term TES in building elements)

Use of building mass and development of PCM for integration into building elements, in order to increase the thermal storage capacity, with the aim to increase the share of renewable sources (mostly solar). TRL 7 and higher.

A2 (Short term TES in heating system)

Sensible heat, latent and thermochemical energy storage for a number of heating technologies: solar thermal, heat pumps and hybrid systems. TES to improve system performance or renewable heat share. TRL 3 to 7.

B1 (Seasonal TES in heating system)

Materials, components and system development for mainly thermochemical storage systems. Increase of renewable share up to 100%. Source is mainly solar thermal but also geothermal; for grid flexibility purposes it can easily be extended to solar PV. TRL 3 to 6.

C (Cooling of buildings)
Ice storage is state of the art; development of novel PCM with melting temperatures between 0 and 15 °C. Development of dry cooling technologies. TRL 3 to 9.

D1 (TES in the building or near the building)
Development of TES systems to provide flexibility in electricity grids and heating networks, included heat sinks for surplus (renewable) electricity and for heating networks optimisation. System control optimisation is an important development aspect. TRL 3 to 9.

D2 (TES far away from the building)
Development of TES systems to provide flexibility in electricity grids and heating networks, included heat sinks for surplus (renewable) electricity and for heating networks optimisation. In this sub-category the TES system is placed somewhere else, far away from the building. D2 differs from D1 in size of the TES system and ownership. A broad range of storage temperatures is addressed, depending on location of TES. Control optimisation is an important development aspect. TRL 3 to 9.

A large group of experts is collaborating in the IEA SHC/ECES joint Task58/Annex33 on "Material and Component Development for Thermal Energy Storage" and in a number of other Annexes in the IEA ECES.

3. Technical discussion

The identification of the development and innovation needs starts with a view on the importance of the different TES technologies in future, for the identified application areas. Then, an inventory will be made of the main developments and innovations that are needed to bring the technologies to the appropriate level of application, in order to accelerate the delivery of affordable and low carbon heating and cooling for buildings. Indicators have to be defined along which the developments could be monitored: when will the development be successful? And finally, the enabling and blocking aspects for every development have to be identified, with possibly the ways to overcome the blockers and to promote the enablers. Needless to say, a large consensus among the Members on the key findings is an essential element of the work.

Table III: Consecutive steps to determine targets and approach for TES R,D&I

Step 1	Target 2030
	What will be the performance of the TES technologies in every application? (description in terms of power, efficiency, size, cost, temperatures, ...) What is the importance or impact of the TES technologies in every application?
Step 2	Research, Developments and Innovations needed
	What is the R,D & I needed to reach the targeted performance? Break down in developments for materials, components and systems

Step 3	Indicators to monitor progress
	What are the typical Key Performance Indicators per application (for example, TRL is indicator for the stage of development) Which other indicators can be utilised?
Step 4	Enablers and blockers
	What are the major barriers and the major enablers (policy, incentive, new business models)

4. Next steps

Once a first overview of the targets, technology R,D&I, progress monitoring indicators and enablers/barriers is made, a prioritisation of the technologies with the highest impact has to be made, taking into account the possible collaborations and interactions with other Priority Areas.

It will be discussed what next steps are needed to achieve these targets and what should be the milestones for the coming year.

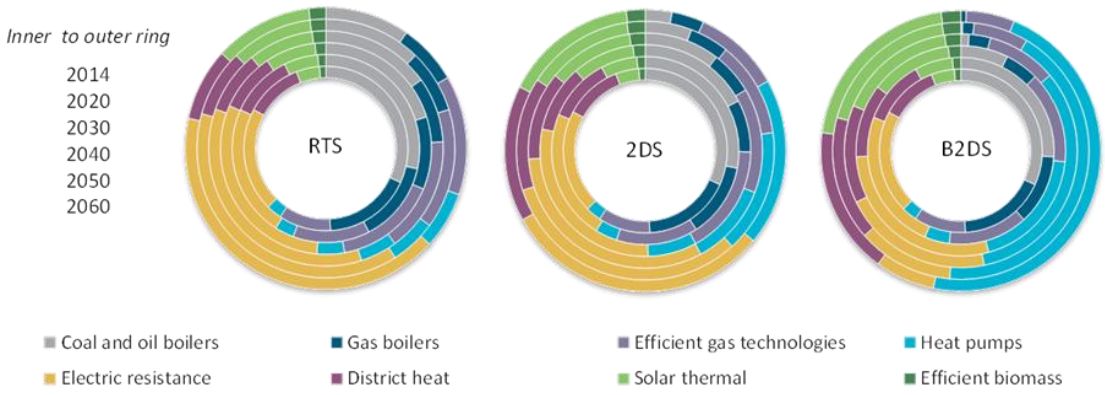
Priority Area B: Heat Pumps

Draft Technical paper for workshop preparation Abu Dhabi, 1-2 Nov 2017

1. Introduction

Globally, buildings account for almost a third of final energy consumption, with space heating and cooling (H/C), and the provision of hot water, accounting for approximately half of this consumption. There is a limit to the reduction in demand that can be achieved by energy efficiency methods alone so low carbon forms of heating and cooling are also required. Direct forms of heating, either burning fuel or resistive heating using electricity can never by more than 100% efficient. Heat pumps however, which consume energy in moving heat from one location to another, rather than generating heat, do not suffer from the same limitations and can achieve coefficients of performance (a measure of heat output for a given energy input) significantly greater than 1.

The IEA has developed three scenarios (Reference Technology, 2 Degrees and Beyond 2 Degrees) which chart the penetration of different technologies out to 2060 given increasing levels of decarbonisation. These suggest an increasing penetration of electric heat pumps with efficient gas technologies (including gas heat pumps) playing an important role in the 2 Degrees Scenario.



Heat pumps are not a new technology and electrically driven have been developed over many years to provide a balance between cost and performance. Many experts argue the scope for a step change in performance i.e. a doubling of the coefficient of performance is impractical. Instead developments are focused around reducing the use of refrigerants with greenhouse warming potential, higher temperature outputs and evolutionary improvements to overall performance.

Gas or thermally driven heat pumps offer more potential for transformative change. In most parts of the world which use significant amounts of gas for heating, gas is substantially cheaper than

electricity. Thus a gas driven heat pump offers the potential to deliver greater cost savings and hence be more affordable than switching to electricity. While a gas driven heat pump is not a zero carbon solution, as an interim step it could cut emissions from gas fired heating by half. Coupled with use of a decarbonised gas (biomethane / hydrogen) such devices could deliver a completely decarbonised solution.

Hybrid heat pumps combine heat pumps and another form of heating in a single system. For example an electric heat pump coupled to a gas boiler; with the gas boiler providing power at times when electricity supply is limited or at peak heat demand, typically when the sink temperature is too low for efficient operation. An alternative form of hybrid is a combination of gas fired CHP and heat pump, where the CHP provides both heat and power to run an electric heat pump generating additional heat output; effectively another form of gas driven heat pump.

2. Status of research

Ten member countries responded to the survey outlining research they were conducting or intending to conduct relevant to the heat pump priority area. The research can be broadly categorised into six areas:

- Performance Improvements
- New refrigerants
- Thermally driven heating and cooling
- Application specific solutions
- Systems integration
- Modelling

It should be noted that surveys of this nature can over emphasise the importance of one topic over another. In this case however the responses cover over 70 individual line items and there was a broad spread of responses in each area. These are discussed further below:

<u>Performance Improvements</u>

Although electrically driven heat pumps are a relatively mature technology, there appears to be significant scope to continue improving their performance. Recent and ongoing research includes cost reduction, noise abatement, higher temperature and multi-stage heat pumps, improved borehole design and the use of different technologies such as Stirling engines.

Assessment of potential impact – for debate:
Potential for performance improvements: 20% increase in COP
Potential for cost reduction: 20% reduction in equipment costs; 30% reduction in installation costs

New Refrigerants

There is still considerable focus on developing heat pumps that operate using refrigerants with substantially reduced global warming potential driven by international agreements to phase out F-gases. These include natural refrigerants such as CO2 and hydrocarbons. Work includes developing and testing new refrigerants and characterising their performance and developing heat pumps and heat exchangers that minimise the use of potentially dangerous refrigerants such as propane. A related thread of research focuses on developing new secondary fluids with improved corrosion resistance.

Assessment of potential impact – for debate:
Important from environmental perspective but unlikely to positively impact affordability or performance

Thermally Driven Heating and Cooling

Gas driven heat pumps have the potential to substantially reduce emissions; in countries where gas is cheaper than electricity they can do so more cheaply than electric heat pumps notwithstanding the substantially lower coefficient of performance. Research is being undertaken on various forms of sorption systems including gas absorption heat pumps of various sizes, desiccant chillers, adsorption air conditioners, desalination plants and thermal transformers.

Assessment of potential impact – for debate:
In areas with a gas grid, methane fuelled heat pumps replacing traditional gas boilers could reduce gas use and emissions by 30%. Such an approach would only be an interim step unless the gas grid was decarbonised but could provide a transition path.

Application specific solutions

Several nations included research targeted at very specific technical challenges in specific applications. This included refrigeration technology for the diary sector in Australia and Sweden; technologies for efficient refrigeration in off-grid communities and fishing boats; direct replacement for a combination-boiler requiring no hot water tank or thermal store; and improved energy efficient and smart refrigeration systems for supermarkets. Systems of varying sizes ranging from very low cost low power systems for near zero energy buildings, systems of the same shape and volume as the traditional systems they are replacing for domestic properties, larger capacity heat pumps district heating solutions and potentially higher temperature systems for industrial processes.

Assessment of potential impact – for debate:
Systems tailored to specific niche solutions are unlikely to deliver major impact in carbon or cost terms except potentially in the domestic sector where quantity could be substantial.

System Integration

Although the integration of different technologies is covered specifically in the Building Level Integration priority area there were a large number of heat pump related projects identified by many nations that deserver particular mentions. These include: solar thermal collectors integrated with heat pumps; thermal stores integrated with heat pumps, underground thermal stores driven by reversible heat pumps and integration of PV to provide the primary power. In addition to equipment integration, research is also being undertaken on how best to control such systems and how to integrate them into the grid most effectively to provide system level balancing and other demand management services.

Assessment of potential impact – for debate:
It is not clear how much impact more successful integration of different components might have but it is likely to be substantial. Impact on performance >50%, impact on capital cost >10%

Modelling

While there were limited projects focused specifically on modelling, in practice modelling provides a substantial underpinning basis for most of the research described above. Many of the projects will be developing improved models as part of the project to test concepts, capture learning and understand wider system level issues. The terminology here refers to traditional static models and dynamic simulations that can be used to identify effective control strategies and efficient systems designs.

Assessment of potential impact – for debate:
While modelling is an important enabler of new capabilities, by their nature models do not deliver measurable impact on environment represented by the model.

3. Technical discussion

The original IC#7 Work Plan for this Priority Area identified 9 "needs" where we needed to target heat pump innovation:

- Improve affordability
- Increase efficiency
- Improve integration
- Reduce technology size
- Improve the user's experience
- Enhance uptake (new business models)
- Increase performance of thermally-driven heat pumps
- Encourage the use of new refrigerants
- Transfer lesson learned between applications

Mapping the research identified above against these needs suggested at a top level these are fairly well covered. Improving affordability is not a major focus; however this is potentially because the majority of researchers are academic institutions rather than manufacturers designing to a cost. Enhancing uptake using new business models, or by better consumer engagement, is also less prominent in reported research. It is not clear whether there is significant read across between heat pumps developed for different applications; however this is more of a means than a need.

At a deeper level there may be a number of other areas where there is only limited research and the potential for greater impact.

Priority Area C: Non-atmospheric Heat Sinks and Sources

Draft Technical paper for workshop preparation Abu Dhabi, 1-2 Nov 2017

1. Introduction

Heat sinks and sources mechanisms and conditions can have significant effects on the energy efficiency of heating and cooling systems. For conventional air-cooled air conditioning (AC) systems in hot climates, heat rejection into high ambient air temperatures detrimentally affects system efficiency. Similarly, in cold climates where heat pumps are used for heating, the energy efficiency is penalized due to heat being sourced from low ambient air temperatures.

The use of different methods for heat sinks and sources can significantly increase efficiency of the different heating and cooling systems, resulting in lower energy consumed and lower carbon emissions. In hot climates, heat rejection to cooler heat sinks has the potential to significantly increase air conditioning system efficiency. This could be done through different mechanisms of heat rejection such as wet cooling tower, ground coupling (shallow geothermal), seawater among other technologies. Similar mechanisms (i.e. ground coupling, wastewater) can also be applied for heat pump systems in heating applications, enhancing system efficiency in cold climates.

2. Current Status of Research

An interest questionnaire was launched in May, 2017 to gather interests of countries in different priority areas. Six countries responded to this survey declaring their interest in making a significant contribution to the Non-Atmospheric Heat Sink and Sources priority area. These countries were United Arab Emirates, Australia, China, Italy, Saudi Arabia and Sweden. Other countries declared, through the survey their interest to be informed about developments in this priority area. These countries included the United Kingdom, Brazil, Canada, Finland and the European Commission.

This shows over 70% interest rate in the priority area from respondents to the Interest Questionnaire.

Secondly, a research and innovation survey was sent out in August, 2017, asking members of IC7 to highlight key innovation priorities and research implemented or planned in their respective country. Through this survey, 9 countries highlighted research and innovation projects that could contribute to this priority area; Australia, Canada, Germany, UAE, Saudi Arabia, Netherlands, UK, Sweden and Denmark.

There was a focus on several technologies in projects highlighted through the survey which as a summary included:

- Indirect evaporative cooling technology (evaporation as cooling technology)

- Geothermal heat rejection
- Ground source heat pumps (multiple U-pipe heat exchangers, CO2 as refrigerant)
- Cold climate air source heat pumps (ejectors integration/ refrigerant mixtures utilization)
- Heat management strategies for PV thermal systems
- Evaluation of heat pump water heaters for cool climates
- Encapsulation of phase change materials to be used as latent heat storage.
- Geothermal Informal System (improve accuracy of geothermal system predictions)
- Geothermal Air Conditioning
- Geothermal District Cooling
- Evaporative Condenser System
- Solar Desiccant Air Conditioning System
- Efficient defrost of air coil evaporators
- Increasing efficiency of refrigeration systems and heat exchangers in supermarkets
- Surface coatings on heat exchangers
- Re-use of waste heat (i.e. to heat greenhouse)
- Combination of CSP with Biomass fired boilers and ORC plant.

The total number of projects for Non-Atmospheric Heat Sinks and Sources highlighted through the survey was 30 with some projects covering the same technology area from the list above.

3. Challenges

Air-based heat sink and source performance can be characterized with generally easily accessible data (air temperature and humidity). When alternative heat sink and source are utilized, the performance characteristics are site specific, and generally require data of higher complexity and more difficult accessibility for an accurate performance estimation.

Taking the shallow geothermal example, soil composition/properties, water content/flow and the underground temperature are some of the crucial parameters required for system design. Measuring these parameters requires specialized site surveying and a detailed analysis of borehole heat exchanger, simulation of underground conditions and geothermal testing (Thermal Response Test, T-Log).

The added complexity of system design and the increased installation cost compared to air-based systems, are the main barriers for the wide adoption of shallow geothermal systems.

In order to reduce such complexity, developments in the following areas are needed:

- Assessment and mapping of system performance

- Prediction of soil temperatures
- Integration with energy management systems
- Quantification of exploitable shallow geothermal energy
- Characterization of advection and dispersion heat transport mechanisms
- Simulation and prediction of operating conditions
- Integration with solar and other RES
- The effects of seasonal variations in rainfall and on the aquifer
- Mitigation of calcium carbonate and silica scales in geothermal systems
- Seasonal optimization of energy extraction

Some other non-technical challenges are:

- Public Knowledge and Acceptance of Geothermal
- National Policy & Regulations
- Lack of accurate assessment tools
- Lack of awareness of Customers and Planners
- Lack of Financial Support & Innovative Business Models
- Labor capacitation

Given the specificity of each different technology, similar challenges apply to all non-atmospheric heat sinks and sources and KPIs should be developed in order to track progress in this field.

4. Technical Discussion Points

Discuss the suitability of ground source/sink, waste water and sea/lake water for cooling and heating in different countries.

Discuss applicability to hot water production using heat pump

Priority Area D: Predictive Maintenance & Optimization Priority Area

Draft Technical paper for workshop preparation Abu Dhabi, 1-2 Nov 2017

1. Introduction

1.1 An Enabling Technology Revolution

Building heating, ventilation, and air conditioning (HVAC) systems typically consist of a range of devices and sensors, all hard wired into a local control system. Robust digital controllers continuously monitor indoor conditions and control certain HVAC equipment components in order to reliably maintain indoor conditions within acceptable comfort tolerances.

A building automation system is often deployed in larger buildings to assist with visualisation of building operation (including historical trend logging) and to enable facilities managers to adjust operational settings. Building automation systems have always allowed on/off operation of building services to be adjusted according to varying occupancy schedules. Increasingly sophisticated algorithms have been introduced into building automation systems, to optimize energy consumption and to support facilities managers.

Building automation systems now routinely upload building data into the cloud, generally via a communications gateway. This enables remote viewing and data processing, which has proved extremely useful, at enterprise level, for monthly environmental sustainability reporting and asset benchmarking.

With building data now available in the cloud, it has become feasible to use data mining, artificial intelligence, machine learning and other data science approaches to both reduce energy consumption, and to provide a range of other bundled building services (e.g. predictive maintenance). These opportunities are further advanced by the emergence of low-cost, internet connected (IoT) devices, which offer the potential for more granular and more diverse data. Mobile devices also provide rich opportunities for engaging with occupants, and complementing data coming from installed devices in buildings. Facilities Managers are increasingly looking to data and data analytics to differentiate their service.

In a recent technology foresighting report, 150 HVAC industry professionals identified that the integration of operational technology systems with information technology systems (OT/IT convergence), in building controls, would have major impact on industry progress towards zero energy buildings.

1.2 Energy Saving Opportunities

Data driven building operation has the potential to dramatically reduce energy consumption and support the integration and adoption of variable renewable energy sources. Some opportunities (not exhaustive) include

- Predictive Maintenance: Poorly maintained, degraded, and improperly controlled HVAC equipment can waste up to 30% of the space conditioning energy used in buildings. Indeed many buildings are poorly commissioned from inception such that they never operate as designed. Data analytics, and machine learning tools, have the potential to provide owners and facility managers with tools to identify incipient problems, predict when they will require maintenance, and provide advice to help rectify these problems. This knowledge coupled with optimization methods enables a more proactive approach to maintenance that can significantly reduce maintenance costs for a given level of service.
- HVAC Energy Optimization. The HVAC system in large buildings is complex, with a large number of interacting equipment parts and many unique situational constraints (e.g. building design, occupancy, climate), which all influence energy consumption. On the principle of "you can't manage what you don't measure", data can empower performance benchmarking and performance forecasting. Data analytics can be used to customize and "self-tune" control strategies to reduce building energy consumption and optimize performance. Occupant experience can also be improved, as a co-benefit, through increasingly localised data and smart controls.
- Demand Response. The inherent thermal storage available in buildings provides a low cost opportunity for managing the variability of the solar energy resource, and for shifting load to take advantage of time-of-use electricity pricing structures. With increasing internet-connectivity, buildings could also provide a stabilizing resource in the electricity grid (linked to IC#1). More granular sensing and controls can maximise demand response capacity while managing occupant comfort expectations.

1.3 Barriers to Innovation

The building construction industry is known to be risk averse and highly sensitive to capital cost. Furthermore, energy is often a secondary consideration, which is compounded by significant split incentive barriers and information asymmetries between tenant, building owner and developer. The ability of data driven innovation to simultaneously satisfy multiple (bundled) services (maintenance, energy, security, lighting etc) is a big advantage for driving market adoption.

The cost of data capture, and the complexity of implementing data analytics services, have also posed significant barriers to implementation in the past. Anecdotally, most of the advanced features of a traditional BAS are rarely used, and there is a relatively small pool of skilled facilities managers capable of fully utilising the various proprietary BAS platforms and understanding bespoke building control strategies. Low cost IoT and IT/OT convergence trends, artificial intelligence based diagnostic support for maintenance staff, and standardization of industry data protocols, all have the potential to reduce these barriers.

If data driven "energy-as-a-service" innovation is to succeed in buildings, then concerns around security and the privacy of data must be addressed. Issues of HVAC management, and fail safe operation, in the event of loss of connectivity must also be addressed if IoT technology is to play a role in real time operation of buildings.

1.4 Research streams

The structure of the Predictive Maintenance Priority Area is divided into the following two enabling streams. These streams are chosen to reflect general research areas rather than specific application solutions. This gives space for researchers to innovate and identify their own opportunities (noting that success will likely result from bundling many applications):

1. Low cost, diverse and granular building operation data: The aim of this research stream is to develop techniques to increase the quality and diversity of data and reduce the cost of acquiring the data that underpins predictive maintenance.

2. Data analytics and mathematical modelling for building applications: The aim of this research stream is to develop energy saving data analytics and mathematical models for predictive maintenance and energy optimization

2. Research Challenges and Directions

2.1 Low cost, diverse and granular building operation data

Data sets and meta-data sets of potential interest (not exhaustive) include (i) equipment operation state data, (ii) indoor conditions data (temperature, humidity and other comfort data), (iii) energy data, (iv) building design (BIM) data, (v) weather data, (vi) building occupancy and occupant data and (vii) historical commissioning and maintenance data. Some of this data is available from the building automation system via a gateway, some is available from the internet, and some will require additional sensors or automated input.

New low-cost IoT sensors should be developed to increase the diversity and quantity of new data streams, leading to increased reliability and occupant satisfaction, with the potential to enable more sophisticated data analytics. Low cost, non-invasive heat flow sensors would be a breakthrough for more granular detection of energy waste.

Research is also required to further develop open standards for data acquisition (eg BACnet) to avoid lock-in to proprietary systems. Common descriptive schema's (eg Project Haystack) are also required to reduce the cost of manual setup and point mapping, and facilitate generalisation of algorithms across different buildings. NIST estimates that the U.S. building industry loses $15.8 billion annually due to lack of interoperability standards.

Data management platforms should provide time series data-storage, and storage of associated meta-data, to enable pattern recognition and model based forecasting. With the advent of increasingly diverse data sets (including text based data), new techniques will be required for "data federation" to automatically discover data relationships and enable data to be compared at different physical and temporal scales.

It should not be forgotten that most buildings have relatively unsophisticated HVAC systems and controls, operated with a "fix it when it breaks" mind-set. Standardization of low-cost, open-access data streams for simple split-system and DX air conditioners could enable predictive maintenance at much smaller scales.

Table 1. New and/or emerging Data Acquisition and Federation Products and Services

Technology	**Estimated TRL**	**Example of Development Efforts**
Smart Sensors and Sensor Systems		Libelium; EnOcean; HUX Connect
Building Specific Cloud Based Data Platforms		Schneider Electric; Johnson Controls, Siemens Building Technologies, Switch Automation; BuildingIQ i5; Enlighted; Equiem;
Generic Cloud Based Data Platforms		ThingWorx; Microsoft Azure; Amazon Web Services; Google Cloud
Smart Building Gateways		Tridium; Infinite Automation
Data Federation Tools & Services		CSIRO Data61, SensorFact

2.2 Data analytics and mathematical modelling for building applications

A wide range of data analytics based services are feasible once data is available. Some examples (not exhaustive) include:

- *Fault detection and diagnosis (FDD)*. FDD algorithms are used to screen HVAC equipment operational data to detect system performance changes, and to diagnose possible equipment failure events that could explain it. FDD is an automated advisory service, the output of which is manually actioned by the facilities manager/ maintenance contractor. FDD can be achieved by rules based analysis; where symptoms have a range of potential physics based causes. The rules are pre-determined based on fixed logic. Smart algorithms can be added to learn from past mistakes. Alternatively, various data-mining and machine-learning techniques can be used in so-called black or grey box methods. In this case, algorithms are trained on data representing normal behaviour/performance of the system, and thereafter equipment data can be screened to detect variations reflecting abnormal operation. The aim is to maximise detection and diagnosis of faults while minimising false positives that create unnecessary work for the maintenance contractor.

- *Predictive maintenance and prognostics*: seeks to predict HVAC system and equipment performance degradation, usually employing a mixture of stochastic process modelling and physical knowledge. It aims to estimate the future performance of the equipment (e.g. time when an unacceptable level of performance will occur), the rate of degradation, and the nature of the failure if it were to occur. This future degradation will be coupled with appropriate cost models to plan future operation and maintenance interventions to minimise energy while maintaining thermal comfort.
- *Supervisory HVAC control*: Control systems normally operate in real-time, responding to the immediate conditions being experienced by the building. With foreknowledge of upcoming conditions (weather, occupancy etc), the HVAC system can be controlled to take alternative, more-effective action. For example, it may be unnecessary to switch on heaters first thing in the morning, if the building is soon to be switched into cooling mode. Machine learning algorithms can be used to understand expected building/occupancy behaviour, allowing model predictive supervisory control signals to provide optimised operational schedules for HVAC equipment. Occupants can be engaged, such that occupant satisfaction and perceived comfort could be used to dynamically optimize control set points and operating modes.
  Optimization can be for local energy optimization outcomes or for Building-to-Grid electricity system optimization. It should be noted that supervisory control requires access to the building automation system to overwrite control setpoints.
- *Self-correcting/fault tolerant controls*: Self-correcting controls are control systems that automatically compensate for degradation in sensors, actuators, control code, control parameters and physical equipment. They aim to identify and compensate for these faults so that near optimal operation of the HVAC system can be maintained.

Potential exists for a myriad of innovation opportunities to be explored using data science in these, and other, predictive maintenance & optimization applications. A crowd-sourcing App-development approach with synthetic/building emulator data sets could be used to help drive innovation.

Not all innovations will require advanced mathematical manipulation. Novel ways of representing the data in graphic user interfaces (dash boards) that drive user comprehension and user engagement should be explored. This could potentially leverage behavioural economics science.

Table 2. New and/or emerging data analytics products and services

Technology	**Estimated TRL**	**Example of Development Efforts**
Automated FDD for building systems		NRCan's CanmetENERGY, CSIRO; University of Wollongong; Drexel University; NIST; PNNL; EcoCentric, Coppertree Analytics; KGS Buildings; UCTriX/DABO; CIM Enviro; Synengco; Skyspark, Masdar Institute
Predictive Maintenance / Prognostics		Purdue University; NRCan's CanmetENERGY, CSIRO; SBRC University of Wollongong; QUT

		Asset Institute; Drexel University;
Supervisory Control for HVAC Systems		CSIRO; NRCan's CanmetENERGY, University of California, Berkeley; University of Sydney; Drexel University; BuildingIQ; EnerNOC; Schneider Electric, STEM; Gridpoint, Zen, Comfy; Honeywell Connected Services, MeteoViva
Self-correcting controls		NRCan's CanmetENERGY, PNNL

Priority Area E: Building-Level Integration

Draft Technical paper for workshop preparation Abu Dhabi, 1-2 Nov 2017

1. Introduction

1.1 Challenges

Globally, buildings account for more than 30 % of final energy consumption, with space heating and cooling (H/C), and the provision of hot water, accounting for well over 80 % of this consumption. Space cooling is a fast growing sector. The heating demand will remain significant.

- Residential buildings are long-lived and have significant space heat loads
- Population, household numbers and service sector activity will grow significantly faster in emerging economies than in developed economies
- In emerging economies, cooling loads are generally more important than heating and are expected to grow rapidly.

More than half of new buildings additions to 2060 will be built over the next 20 years, and by 2035 nearly two-thirds of the global buildings stock to 2060 will already be standing. Immediate steps must be taken to avoid lock-in of inefficient buildings and address energy demand from long-lived buildings assets. High performance buildings construction and deep energy renovations of existing buildings play a critical role in reducing building energy demands.

In addition to this, the building sector is extremely fragmented along: i) Local climatic conditions, ii) Technologies, iii) Age of installed stock, iv) Energy sources exploited and v) Culture and behaviour.

Most of the energy demand for H/C is currently satisfied with fossil fuels (natural gas, fuel oil and coal) with far less use of renewable energy sources. This is due to various obstacles, ranging from technical, financial, legal, social, and cultural.

Residential and commercial buildings are built to provide comfort for their occupants. These occupants demand specific temperature and humidity levels and, when coupled with the variation in external temperature and humidity, and the characteristics of the building fabric, this defines the annual energy demand. This will have an impact on the possibility of using the building as an energy storage medium to increase flexibility as well as the designed capacity for H/C systems and their annual efficiency performance.

In order to find the most efficient and sustainable solution it is important to take a system approach; starting with 1) high performance building envelopes and envelope components (e.g. air sealing, insulation, windows), then installing 2) efficient equipment for appliances, lighting

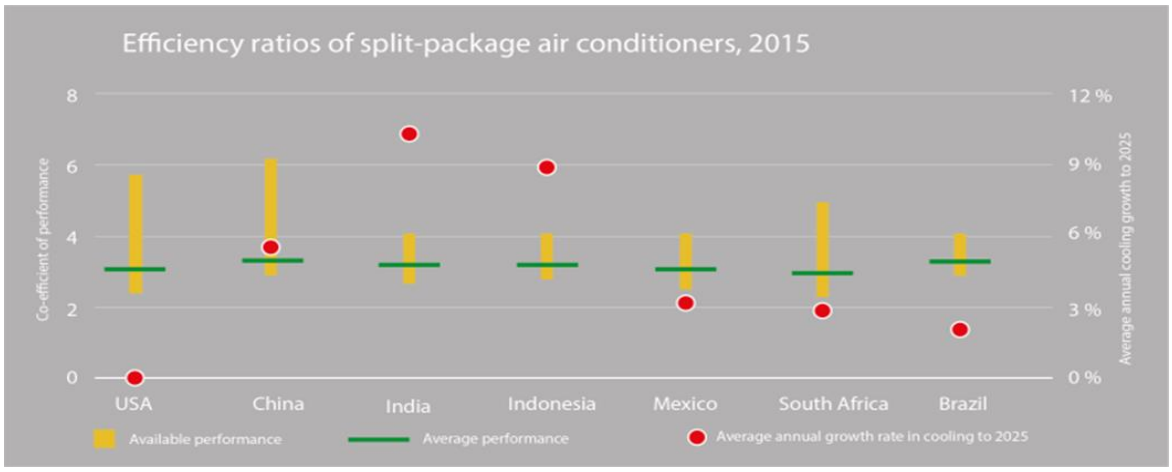
and cooking, 3) efficient H/C equipment and 4) efficient water heating systems. Energy efficiency improvements should be considered an integral part of any building upgrade and it is important to address these first before considering the H/C equipment.

The lifetime of building envelope and building envelope components are, in general, very long by comparison with, for example, lighting and appliances. It is therefore important to have a strong focus on building integration in new buildings to enable future innovative H/C systems and avoid lock-in effects. In addition, it is important to find affordable retrofit solutions for existing buildings which can enable new innovative H/C system solutions. In the transformation to a sustainable building sector the lifetime of different systems and components in buildings has a large impact on the possibility to refurbish/replace old components and systems. Furthermore, this lifetime will influence the indirect CO2 emissions from the manufacturing phase and the life-cycle cost for the end user.

Example of lock-in effects are: 1) buildings without a central distribution system (air or water) in the building for heat/cooling or 2) distribution systems for heating and cooling with undersized heat exchangers. As an example a building can be designed with a heat distribution system which needs 95 °C to achieve an air temperature of 22 °C in the room. In order to develop and deploy innovative, affordable and more efficient heating and cooling, systems with a smaller temperature difference are needed, which will require larger heat exchangers.

1.2 Energy Saving Opportunities - Examples

- Poorly maintained, degraded, and improperly controlled HVAC equipment can waste up to 30 % of the space conditioning energy used in buildings.
- The potential to upgrade waste energy in urban areas is huge, e.g. from cooling systems in residential and commercial buildings, industrial processes, metro etc.
- Combining off peak electric heating and a thermal store can significantly reduce demand for high cost, high carbon peak time electricity.
- Using a gas CHP system to power an electric heat pump can produce the effect of a gas driven heat pump with a coefficient of performance of over 2.
- Efficient pumps, fans and storage can increase the efficiency of the heat pump system by up to 20-30 %.



- Heat pump system for heating, cooling and hot water production can reach annual coefficient of performance of 5-7. The figure above indicates that the need for cooling will grow in warm and humid climates. It also shows the potential of using the best available technology for air conditioning.
- Waste heat from air conditioning systems is not utilised. It would be possible to use the waste heat in a low temperature thermal grid for hot water in combination with heat pumps. Added value will be less "heat island effect" in dense urban areas.

1.3 Barriers to Innovation

The building construction industry is known to be risk averse and highly sensitive to capital cost. Furthermore, energy is often a secondary consideration, which is compounded by significant split incentive barriers and information asymmetries between tenant, building owner and developer.

Existing infrastructure, building standards, metrics, energy mix, end use behaviour and culture can be barriers for decreased energy demand and deployment of new system solutions.

System boundaries can be a barrier for deployment of new system solutions; depending on the boundary, different system solutions can be more or less attractive and competitive. In addition, existing business models can be a barrier to fitting for the most energy efficient systems solution at a building level and limit the opportunities to use and upgrade waste heat at a building or district level.

Those in the value chain have different interests and knowledge. In order to find sustainable solutions it is important to evaluate both the upfront cost and the life-cycle cost.

Furthermore, the heating demand, cooling demand and hot water demand vary for different types of buildings and climates and there are large differences between residential and commercial buildings. In general, internal heat loads often have a much larger influence in commercial buildings on the overall energy demand, e.g. even in cold climate there is a need for cooling down to outdoor temperatures of -10 °C. The situation in new buildings differs from existing buildings and several barriers influence decisions to make larger retrofits in the building when H/C systems should be refurbished.

1.4 Research streams

The structure of the Building-Level Integration Priority Area is divided into the following two enabling streams. These streams are chosen to reflect general research areas rather than specific application solutions. Both levels need to be considered. This provides space for researchers to innovate and identify their own opportunities (noting that success will likely result from bundling many applications):

1. *Building level*: The aim of this research stream is to develop integrated techniques and system solutions on a building level.

2. *District level in dense urban areas*: The aim of this research stream is to develop techniques and system solutions on a district level. The district approach includes both electric grids, gas grids and thermal grids (district heating and cooling).

2. Needs for RDD&D

Nine member countries responded to the survey outlining research they were conducting or intend to conduct, relevant to the building level integration priority area. The research can be broadly categorised into the following four areas:

Decreased energy demand and increased energy savings at a building level

- Building energy performance modelling/simulation software tools to assess and optimize the integration of different combinations of heating and cooling systems and increased use of renewable.
- Strong reduction of the energy demand for heating, cooling and appliances in the building stock. Integrated approach for heating, cooling and ventilation.
- Combinations of two or more low carbon technologies; e.g. heat pumps and thermal storage
- Retrofit solutions for existing buildings
- Low temperature systems for heating and high temperature for cooling

Increased flexibility at a building level

- Increased knowledge about accepted indoor comfort (temperature and humidity) to increase flexibility at a building level
- Increased thermal mass/time constant at a building level to increase flexibility while maintaining an acceptable indoor climate (temperature and humidity).
- Integration of compact energy storage in H/C systems

Decreased energy demand and increased energy savings at a district level - high density urban areas

- New generation - Low temperature district heating with heat pumps
- Increased use of waste heat from industry and buildings
- Integration of CHP, bio fuel, gas boilers, large scale heat pumps and possibly solar thermal.

Increased flexibility on a district level - high density urban areas

- Storage - annual, monthly or hourly
- Cluster of heating and/or cooling units

3. Technical discussion

Where do there appear to be gaps in the coverage of existing research that we need to fill? Suggest the sort of targets that might be considered to track progress.

Choice of heating and cooling systems is dependent on the total energy demand and the relation between heating, cooling and hot water demand. It is different enablers and barriers for residential and commercial buildings. Is it possible to map/update the design rules-of-thumb for H/C systems in different building typologies in different climate zones to identify optimum combinations? Design engineers need to be engaged with Architects in developing creative solutions involving the integration of building envelope and H/C. As we move progressively lower energy consumption targets, the H/C equipment could not be treated in isolation from the Building services engineering system and the Architectural design. Would it be possible to make a simplified map including different building typologies and different climate zones to identify innovative, affordable and efficient H/C solution taking into account outcomes from priority area A to D?

Different enablers and barriers can have more or less impact on new buildings and for retrofit of existing buildings. Is it possible to define important research actions and innovations to avoid lock-in effects that will have an impact on acceleration and transformation to affordable, efficient, low carbon H/C solutions?

Crosscutting approach often adds value, with room to channel and integrate relevant activities from the other Priority Areas. Outcomes from the other priority areas will probably benefit and add further value to having a building integration approach. Digitalization can also provide new possibilities to improve efficiency, affordability and robustness of H/C systems. Additionally the potential to use thermal mass/time constant in the building, in combination with other storage solutions needs to be evaluated. The overall system efficiency of heat pumps systems can increase by taking an integrative approach. Similarly, we should undertake more research on H/C systems in combination with storage.

Buildings integration or district level integration approaches can increase possible energy savings, increase use of waste heat and increase flexibility, which is of important for further use of renewable energy. Sector coupling: taking into account that heating and cooling system become part of broader energy system where (electric) mobility, variable renewable production, P2H, P2P, P2G are all connected through a flexible energy system, including all sorts of storage (electric + thermal) and smart energy management systems on neighbourhood level.

While some research is being undertaken to explore the benefits of combining different low carbon solutions, the effects of close coupling different technologies together does not appear to be systematically explored and could reveal substantial synergistic savings.

Steps to identify targets, important areas for R&D and actions to accelerate transformation of the heating and cooling sector on building and/or district level?

1. **Target until 2030- building level and district level - stimulate acceleration.** Is it possible to define targets which will accelerate transformation to efficient and low carbon heating and cooling? Target first level H/C Solutions contribute to X Giga Tonnes reduction by 2030. Targets second level (efficiency, cost, installed capacity, renewable share, size….)

2. **Research and Innovations needed?** Identify areas which benefit from a building integration or district integration approach to fulfil the targets. Focus on acceleration and transformation to fulfil the targets. Use the outcome from other priority areas.

3. **Define enablers and barriers to overcome on building or district level.** Describe actions or R&D needed to accelerate implementation of affordable, efficient low carbon H/C. (policy, capacity building, incentive, business models……)

4. Is it possible to **define KPI** which can stimulate acceleration? X H/C innovation projects get funding, X R&D project from TRL 2 to TRL X……, X R&D projects demonstrated in X in at least X locations.

4. Next steps.

Once a first overview of the targets, technology R,D&I, progress monitoring indicators and enablers/barriers is made, a prioritisation of the technologies with the highest impact has to be made, taking into account the possible collaborations and interactions with other Priority Areas.

It will be discussed what next steps are needed to achieve these targets and what should be the milestones for the coming year.

Priority Area F: Physiological Studies

Draft Technical paper for workshop preparation Abu Dhabi, 1-2 Nov 2017

1. Introduction

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment. Other than four environmental parameters namely (a) Air Temperature (b) Mean Radiant Temperature (c) Air Speed (d) Relative Humidity and two personal parameter (e) Metabolic rate (d) Clothing, also has impact on thermal satisfaction. Based on thermal environment context, human body rely on two kinds of adaptation to remain in equilibrium. These are (a) Physiological Adaptation (b) Behavioural Adaptation.

While considering investment in high energy efficient, low energy cooling/heating or hybrid comfort system Research & Development – Deployment (RDD), it is important to invest into physiological studies in context of local climate and culture of Mission Innovation (MI) member countries. Such fundamental RDD will develop pathways for technologies and policies to save considerable amount of energy, meeting MI objectives.

Overarching activity framework under title ***'Empirical and Technological Research Investigations for Enhanced Thermal Comfort'*** should be devised for member countries to innovate solutions leading to access to thermal comfort, especially in tropical and extreme climate regions. Keeping building occupant as primary beneficiary, deep RDD will develop pathways for innovative technologies and contextual policies to save considerable amount of energy, meeting MI objectives.

2. Status of research

The survey responses reveal that Canada and India are the two countries consider physiology study as the key priority area under MI affordable heating and cooling of buildings. Canada highlights the aspect of productivity and performance gains as an impact of environmental conditions. India shows interest in the occupant behaviour and increase use of adaptive thermal comfort along with advancement in air motion devices, investigation in enhancing effectiveness of low energy cooling systems – primarily non-compressor based systems and local/personal thermal comfort systems. However, survey conducted as part of MI IC#7 provides partial understanding about current state of work in MI countries. Empirical understanding suggests that number of research projects are underway in UK, Germany, Sweden, Australia and China.

Need for research: It is important to understand physiological adaptation and behavioural adaptation together while developing new technologies. Such work requires multi-disciplinary approach, which may range from subjects such as human physiology, social science to mechanical engineering, which may range from laboratory experiments to field studies. The studies and application in this field can be broadly categorized as:

1. Impact of air movement in enhancing comfort in mixed mode operation (MM), naturally ventilated (NV) and air conditioned buildings (AC).
2. Non-uniform and dynamic thermal environmental exposures, and investigation into the thermal asymmetry.
3. Thermal allesthesia
4. Personalized comfort systems and personalised control

1. Air movement

Laboratory and field studies have demonstrated that air movement compensates for warmer temperatures in making people comfortable. Integration of air movement devices with conventional compressor based HVAC and low energy cooling systems requires additional R&D and innovation. Apart from RDD, it is also important to provide impetus into industrial products and controls.

Optimizing a ceiling fan's parameters such as rotation speed, diameter, blade count, horizontal inclination angle, vertical inclination angle, a preferable flow and thermal field can help in achieving thermal comfort without / with the use of air-conditioning under certain conditions. It enhances the convective heat transfer so that the air flow can effectively take away the heat generated by a human body.

2. Non-uniform and dynamic thermal environmental exposures

Isothermal, uniform and static neutral thermal environments consume large amount of energy at the same time do not provide thermal satisfaction to building occupants. At the same time, more dynamic and non-uniform thermal environment has potential to save energy while providing thermal satisfaction to building occupants, provided one accounts for thermal asymmetry.

There are a variety of conclusions found in the existing research regarding comfort at varying temperatures of skin and body parts which shows lack of consensus in this regard and scope for further study. Thermal environment conditions created by various systems need to be investigated. Process to size and control various (Conventional HVAC, Radiant, Low energy cooling, personal comfort systems) systems needs attention at research and at products level.

3. Thermal allesthesia

Thermal allesthesia is also dominant factor. It refers to sensory thermal pleasure with variation. In transient or non – uniform environments such as environments having presence of hot and cold surfaces, intake of hot/cold beverages/food items, air motion devices, environments having high thermal asymmetry, thermal allesthesia plays major role. An environmental stimulus which has potential to restore human thermal comfort, is considered as very pleasant or positive allesthesia.

- Temperature change directed to a particular body part that is capable of providing the perception of comfort to the whole body can save energy on space cooling as compared to static indoor climates. Even in transitional spaces, or just after arrival in conditioned space, use of thermal allesthesia can help save energy. Detailed study of spatial allesthesia that follow a predictable psychophysiological pattern can help inform the design systems as well.
- Over-cooled or over heated small transitional spaces can help purge excess body heat and bring the body temperature and thus reducing the energy requirement of the large work space. But the study of the required environment condition and duration of exposure to achieve this benefit requires extensive physiological studies.

The challenge is how to design for it in the built environment while there are many examples of allesthesia available in the natural environment.

4. Personalized comfort systems and Personalized control

Control over one's immediate thermal environment also is key to attain satisfaction. Sensor and controls technology must enhance its capabilities to provide comfort conditions based on occupant preferences.

Researches have shown that people in naturally ventilated buildings can be comfortable over wider range of temperatures than in an air-conditioned building. But the degree of control for the provision of natural ventilation has varied impact on the thermal responses.

- Personalized comfort systems such as foot warmers and heated and cooled chairs with personalised controls have proven to be very beneficial in reducing heating and cooling demands in experimental studies but their practical applications needs to be studied.

5. Low energy cooling systems, system sizing and controls.

Non-refrigerant based low energy cooling systems are the most important ones while finding solutions for low carbon and affordable heating and cooling of buildings

- Radiant system is an effective strategy to reduce the mean radiant temperature of a space and thus reduce the cooling and heating requirement. This system can be used as radiant floor, radiant panels and radiant ceiling in a space. Along with the radiant panels if the air velocities are designed keeping in mind the human body segment in the space usage, it can reduce the use of air conditioning. In order to optimize the use of radiant panels for thermal comfort, physiological studies hold enormous importance.
- Evaporative cooling, (two stage or variations of it) is another low-energy cooling system that has huge potential for cutting down the use of refrigerants. It has one of the major components of comfort criteria which is humidity as its integral part. Hence various combinations of direct and indirect evaporative cooling systems is under development and research stage which needs to be assimilated with physiological studies for maintaining indoor comfort conditions.

Annex III: List of Participants

Title	First Name	Surname	Affiliation	Country
Mr	Ammar Abdulateef Abdulhameed	Abdulateef Abdulhameed	SKM Ariconditioning L.L.C	AE
Dr	Afshin	Afshari	Masdar Institute	AE
Mr	Dinesh	Aggarwal	GASCO	AE
Mr	Dinesh Kumar	Aggarwal	ADNOC	AE
Miss	Marwa	Al Awadhi	UAE Ministry of Energy	
Dr	Ali	Al-Alili	The Petroleum Institute	AE
Ms	zainab	Aldhanhani	masdar	AE
Miss	noura	alkaabi	masdar	AE
Mr	Carlos	Amaya	QCC	AE
Mr	Masab	Annaqeeb	Khalifa University	AE
Dr	Marcello	Aprile	Politecnico di Milano	IT
Miss	Maram	Arafat	Masdar Institute	AE
Dr	Peter	Armstrong	Masdar Institute/Khalifa U of S&T	AE
Dr	Monica	Axell	RISE and Heat Pump Centre	SE
Ms	lindita	bande	Bin Salem Holding	AE
Prof	marco	beccali	Università di Palermo	IT
Mr	Teun	Bokhoven	IEA TCP ECES	NL
Mr	Iain	Campbell	RMI	US
Mr	Yong	Chen	Irena	AE
Dr	Michael	Cholette	Queensland University of Technology	AU
Prof	Paul	Cooper	Sustainable Buildings Research Centre (SBRC), University of Wollongong	AU

Prof	Robert	Critoph	University of Warwick	GB
Mr	Piero	De Bonis	European Commission	BE
Ms	Jennie	Dodson	BEIS	GB
Dr	Harald	Drueck	ITW Univerity of Stuttgart	DE
Mr	Philip	Eames	Loughborough University	GB
Dr	Angela	Fandino	Engineering Sustainable Futures	AE
Mr	Michel	Farah	Daikin Midlle East	AE
Dr	Roberto	Fedrizzi	EURAC Research	IT
Dr	Angelo	Freni	CNR - National Council of Research	IT
Mr	Luiz	Friedrich	UAE Ministry of Energy	AE
Dr	Myriam Elisa	Gil Bardaji	KIT	DE
Mr	Ken	Guthrie	Sustainable Energy Transformation	AU
Dr	Richard	Hall	Energy Transitions Limited	GB
Miss	Amal	Hamadeh	Ministry of Energy	AE
Prof	Neil	Hewitt	Ulster University	GB
Mr	Sophie	Hosatte	CanmetENERGY - Natural Resources Canada	AE
Mr	Zisis	Ioannidis	Concordia University	CA
Dr	Gilles	Jean	Concordia University	CA
Dr	BHASKARA VENKATA REDDY	JONNALA	Department of Science and Technology	IN
Mr	Paul	Jordan	Energy Systems Catapult	GB
Mr	Huub	keizers	TNO	NL
Mrs	Kerstin	Krueger	Project Managment Juelich	DE

Dr	Satish	Kumar	Alliance for an Energy Efficient Economy	IN
Mr	Christopher	LaBorde	Trakref	AE
Prof	Robert	Lowe	UCL Energy Institute, University College London	GB
Mr	Luka	Lugaric	Dubai Supreme Council of Energy	AE
Prof	Graeme	Maidment	London South Bank University	GB
Mr	Torsten	Malmdorf	Danish Energy Agency (EUDP)	DK
Mr	Pietro	Menna	European Commission	BE
Dr	Daniel	Mugnier	TECSOL	FR
Mr	Shantanu	Nadpurohit	Siemens LLC	AE
Mr	Jeremy	Osborne	Energy AE	AU
Mr	Miika	Rämä	VTT Technical Research Centre of Finland	FI
Prof	Rajan	Rawal	CARBSE at CEPT University	IN
Mr	Jon	Saltmarsh	BEIS	GB
Mr	Luis	Santos	Masdar Institute	AE
Mr	Ganapathi Subbu	Sethuvenkatraman	CSIRO	AU
Dr	Sgouris	Sgouridis	Masdar Institute	AE
Dr	Marco	Simonetti	Politecnico di Torino	IT
Dr	Alistair	Sproul	University of New South Wales	AU
Miss	Esra	Trepci		AE
Dr	Wim	van Helden	AEE INTEC	AT
Dr	Karl-Anders	Weiss	Fraunhofer Institute for Solar Energy Systems	DE
Prof	Stephen	White	CSIRO	AU