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Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 51

Acoustic Signatures of Heat Pumps

Final Report

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA

The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration, and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or “Annexes”, in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

Disclaimer

The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organized under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

The Heat Pump Centre

A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimize the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organizations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:

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Acoustic Signatures of Heat Pumps

IEA HPT Annex 51

IEA HPT Annex 51
Umbrella Report

April 1st, 2017 – December 31st, 2020

The IEA HPT Annex 51 team.

Date: October 2021	Final Version, Review: 06

1. Contents

Introduction

Reduction of acoustic emissions is important to further **increase the acceptance of heat pumps** as air-to-water, water-to-air, air-to-air and brine-to-water (ground source) units (referred to as "units" in the following text). To increase this acceptance and minimize noise annoyance more focus has to be put on the acoustics emissions at steady state and transient behaviour of acoustic signatures during different operating conditions (e.g. icing, de- frosting, capacity control, cooling mode).

Depending on end user (owner or neighbour), noise is an indoor and/or an outdoor issue. From an acoustic perspective, both new and retrofit markets are important to be considered, as those heat pumps provide a convenient and effective way to exploit the potential energy savings.

Acoustic emissions have to be accessed in a hierarchical approach considering the following levels:

- **Component level** - Low noise components (e.g. fans and compressors)
- **Unit level** - System approach of combining the components, unit control, transient acoustic features.
- **Application level** (building/neighbourhood, including smart grid, psychoacoustic effects & acoustic propagation)

Furthermore, Education and training are very important aspects in heat pump acoustics (placement, noise reduction measures, modes of control and operation) so that bad installations will not go against good acoustic design and construction of the units.

As the current legislation is globally very diverse (also serving the needs of the different locations and countries), the Annex is structured to contribute to guidance and future standards in this field.

This Annex lived through the collaboration from the six countries (given in alphabetical order) Austria, Denmark, France, Germany, Italy and Sweden. All information regarding the IEA HPT Annex 51 "Acoustic Signatures of Heat Pumps" can be downloaded from the IEA HPT Annex 51 Website:

https://heatpumpingtechnologies.org/annex51/

This document contains an overview of the most important content of the different tasks, which had been followed throughout the duration of the Annex. The deliverable documents together with presentations, the webinar video and additional documents can be retrieved from the Annex 51 website. At the end of this document, please find information the the national representatives, conclusions, an outlook and some recommendations.

Deliverable Documents

The following documents contain the deliverables generated by the IEA HPT Annex 51 team during their collaboration:

E	**IEA HPT Annex 51 Executive Summary and Document Guide – IEA HPT Annex 51 Executive Summary and Document Guide**	*E*
U	**IEA HPT Annex 51 Umbrella Report – IEA HPT Annex 51 Umbrella Report**	*U*
1.0	Deliverable 1.0 – **Introduction – IEA HPT Annex 51 D1.0**	*1.0*
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4	Deliverable 4 – **Analysis of the Effect of Operating Conditions of Heat Pumps on Acoustic Behaviour – IEA HPT Annex 51 D4**	*4*
5	Deliverable 5 – **Report on heat pump installation with special focus on acoustic impact – IEA HPT Annex 51 D5**	*5*
6	Deliverable 6 – **Annoyance rating and psychoacoustical analysis of heat pump sound – IEA HPT Annex 51 D6**	*6*
7.1	Deliverable 7.1 – **Educational material on acoustics of heat pumps – IEA HPT Annex 51 D7.1**	*7.1*
7.2	Deliverable 7.2 – **Workshop material and conference contributions – IEA HPT Annex 51 D7.2**	*7.2*

The Webinar

The presentations of the Webinar held on Monday, November 30th, 2020 can be retrieved from the IEA HPT Annex 51 website:

Introduction Annex 51 webinar – Caroline Haglund Stignor (Heat Pump Centre)

Annex 51 overview – Christoph Reichl (AIT, Austria)

European Standards and Legislation – Roberto Fumagalli (Polimi, Italy)

Noise and seasonal variations based on interlaboratory results – Francois Bessac (CETIAT, France), Thomas Gindre (ISE, Germany)

Effect of different heat sinks and operation modes on acoustic emissions – Kamal Arumugam (DTI, Denmark)

(Transient) Noise of Heat Pumps – Thore Oltersdorf (Fraunhofer ISE, Germany)

Heat pump installation and effects on surrounding environment – Christoph Reichl (AIT, Austria)

Annoyance rating and psychoacoustical analysis of heat pump sound – Henrik Hellgren (RI.SE, Sweden)

The webinar can be rewatched here: **https://www.youtube.com/watch?v=tyiMwMhCuSc**

The Workshop

The presentations of the Workshop held in the framework of the 25th IIR International Congress of Refrigeration in Montreal, Canada on August, 29th, 2019 can be retrieved from the IEA HPT Annex 51 website:

Thomas Fleckl, Christoph Reichl, Annex 51 "Acoustic Signatures of Heat Pumps" in the framework of the International Energy Agency Technology Collaboration Programme on Heat Pumping Technologies (IEA HPT), AIT Austrian Institute of Technology

Roberto Fumagalli, Acoustic Regulations of Heat Pumps, Polimi, Italy

Johann Emhofer, Christoph Reichl, 1D modelling of heat pumps including acoustics, AIT Austrian Institute of Technology

Christian Vering, Jonas Klingebiel, Markus Nürenberg, Dirk Müller, Simultaneous energy efficiency and acoustic evaluation of heat pump systems using dynamic simulation models, RWTH Aachen

Christoph Reichl, Peter Wimberger, Felix Linhardt, Johann Emhofer, Acoustic Emissions and Noise Abatement of Air to Water Heat Pumps, AIT Austrian Institute of Technology, (part1) (part2)

Karlheinz Bay, Simon Braungardt, Thomas Gindre, Thore Oltersdorf, Jens Rohlfing, Lena Schnabel, Agostino Troll, Testing campaign on the energetical and acoustical behaviour of a heat pump, Fraunhofer ISE/IBP (part1) (part2)

Ola Gustafsson, Henrik Hellgren, Caroline Haglund Stignor, Heat pump noise – operation dependence and seasonal averaging, RISE Research Institutes of Sweden

1. Task 1 "Legislation and standards"

This task had the purpose of introducing the acoustic theme for heat pumps starting from the fundamental concepts inherent in acoustics and then passing through the instruments and measurement methods, to arrive at a compendium of all the standards, laws, regulations and certification schemes in European area (trying to cover at least all the main European countries). 4 documents have been produced and are briefly listed here.

Deliverable 1.0 – **Measurement Techniques** – **IEA HPT Annex 51 D1.1**	*1.0*
This deliverable answer 2 questions: - What is sound and how does it manifest? - How does human beings perceive sound? This document was created to give a brief description of the main acoustic concepts. It is divided into two parts. The first part answers the question: "what is sound and how does it manifest?" It describes the physics of the acoustic phenomenon, with a brief definition: - of the quantities (pressure, power and sound intensity); - of the methods of propagation of sound outdoors; - of how the sound changes depending on the proximity or distance from the source, or depending on external conditions (wind, thermal stratification, presence of obstacles, diffusion and diffraction phenomena, the ability of some materials to absorb or reflect sound). The second part, on the other hand, focuses on the perception of sound by human beings by answering the question: "how does human beings perceive sound?" In fact, human beings do not hear all sounds in the same way: the hearing behavior is not linear and homogeneous and varies with the frequency and intensity of the stimulus. There are anatomical descriptions of the auditory organs and the laws that determine their behavior, the limits of audibility in terms of maximum and minimum audible sound pressure and maximum and minimum audible frequency, which frequencies are perceived more easily and which are less.	

Deliverable 1.1 – **Measurement Techniques** – **IEA HPT Annex 51 D1.1**	***1.1***
This deliverable answer these questions: - What tools are used to measure the acoustic quantities described in D1.0? - How are the tools used to get useful information on the sound emission of the sources? - How much noise can a human being positioned at point A get if the heat pump is positioned at point B? - How much noise does the heat pump I am measuring emit overall? - Where does most of the sound come from? - How is this sound emitted by that heat pump perceived? / Which do you prefer between sound A and sound B? This document shows the measurement methodologies used. This document is also divided into two large parts. The first part answers the question "what tools are used to measure the acoustic quantities described in D1.0?" and describes the instrumentation used in the measurement campaigns. First of all microphones, their functioning, the composition of more complex instruments such as intensity probes and microphone arrays are described, starting from the combination of 2 or more simple microphones. The first part is completed with the description of sound level meters, analyzers and acoustic calibrators. The second part, on the other hand, answers the question: "how are the tools used to get useful information on the sound emission of the sources?" This part describes: • sound pressure (and sound pressure level) measurements, the simplest possible and the least complete, since its value depends on the reciprocal position of the source and of the microphone. These measurements can tell how much noise a heat pump could produce if measured at a certain distance (but be careful: the configuration of the measurement environment can change the result of the measurement). We can say that this method answers the question: "how much noise can a human being positioned at point A get if the heat pump is positioned at point B?"; • sound power (and sound power level) measurements, much more significant since sound power is an intrinsic property of the source and does not depend on the measurement method. These are the type of measures required by the various certification schemes and labeling operations, since they characterize a heat pump from the point of view of its noise emission. In this the question we want to answer is: "how much noise does the heat pump I am measuring emit overall?"; • the acoustic mappings, made with intensity probes or with microphone arrays. These measurement methods are more oriented towards research and development activities, even in the case of heat pumps, since they easily allow to characterize a sound source in terms of directivity (answering the question: "where does most of the sound come from?"), both in terms of intensity and in terms of frequency. These methods usually allow you to create colored maps to be superimposed on the photos of the acoustic source to search for the most important sound sources quickly and effectively; • psychoacoustic investigations, carried out with special mannequins (HATS, head and torso simulator). These mannequins allow the creation of audio recordings that are very faithful and very similar to the real human perception of the recorded sound events (as long as you listen to these recordings with headphones). Such audio recordings are very useful as they can reproduce exactly the same sound event to many people, without listeners being influenced by: reproducibility of the sound event, other sources of distraction (listening directly to the real sound source could affect the perception of the sound itself: in the case of heat pumps, the judgment with respect to the perceived sound	

quality could be influenced by the aesthetic judgment). In this way, audio tracks referring to different products could be proposed in sequence so that the listener can express an opinion and his preference on the sound heard. The disturbance is not always linked to the intensity of the sound, but also to its characteristics (for example, type of spectrum emitted, sound stability over time,…). Investigations of this type can propose a sound quality index that is more representative of the disturbance than the current use of the simple sound power levels emitted by heat pumps or the pressure levels perceived at the disturbed potential, which are the current legislative approaches that regulate noise in all EU States considered in the ANNEX51. Ultimately the question that psychoacoustic methods want to answer is: "how is this sound emitted by that heat pump perceived?" annoying, pleasant, boring, neutral, disturbing, repetitive ...? Or again: "which do you prefer between sound A and sound B?"

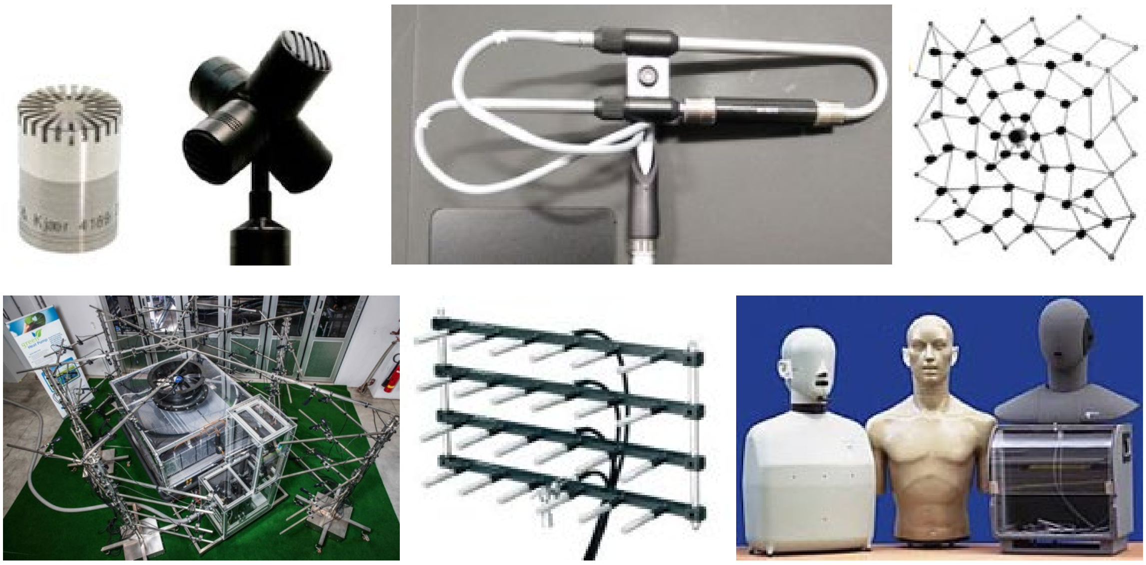


Figure 1-1: *Picture of principal instrument: microphones, intensity probe, microphones arrays, head and torso simulators [Sources: see D1.1]*

Deliverable 1.2 – **Regulations – Countries overview – <u>IEA HPT Annex 51 D1.2</u>** *1.2*

This deliverable answer this question:
How do States, Standards and Regulatory bodies regulate the problem of noise emissions?

This document answers the question: "How do States, Standards and Regulatory bodies regulate the problem of noise emissions?" Both general answers, and answers for the particular case of heat pumps have been given to this question. The main areas covered are 3: international standards; European directivities and Certification schemes; National laws of EU States. First of all there is a description of the international standards that regulate the problem of noise:

- the international product standards EN12102-1 and EN12102-2 are described;
- the measurement standards of the sound pressure level: ISO 1120X family;
- the measurement standard of the sound power level measurement: ISO 347X family and ISO9614 family.

Below there is a description of the European regulations in terms of maximum emission limits and labeling for heat pumps with electric driven compressors (EU 206/2012; EU 626/2011; EU 813/2013; EU 211/2013; EU 814/2013; EU 812/2013) and a brief description of the Ecolabel system. In the document there is also a description of the main certification schemes in EU: Eurovent and HP Keymark.

The document continues with a description of the national laws of the EU States considered in the ANNEX51 project, in addition to information available also from other non EU States (including Switzerland, as it is an important market for the heat pump sector).

The States taken into consideration are:

France, United Kingdom, Austria, Italy, Spain, Germany, Poland, Denmark, Sweden, Finland, Norway, Switzerland, South Korea, Japan.

Deliverable 1.3 – **Regulations – Synthesis** – **IEA HPT Annex 51 D1.3** *1.3*

This deliverable answer these questions:

- How do States regulate noise emissions (from heat pumps)?
- What similarities and what differences between the various States?

In this document an analysis has been made between the various national legislative systems which differ in terms of noise. The analyzes were made taking into consideration different areas:

- environmental noise laws (maximum limits allowed indoors or outdoors, homogeneous areas, periods of the day or days of the week considered, penalties for particular sources such as heat pumps in some cases, or for particular types of noise such as impulsive noises repeated and tonal sounds);
- laws on noise concerning buildings (in some cases maximum limits of systems are defined);
- limits regarding the Safety area (maximum limits allowed in the workplaces).

The question that this document tries to answer is similar to the previous one: "How do States regulate noise emissions (from heat pumps)?" But here the answers have been summarized and organized to favor a comparison and an answer also to the question: "what similarities and what differences between the various States?"

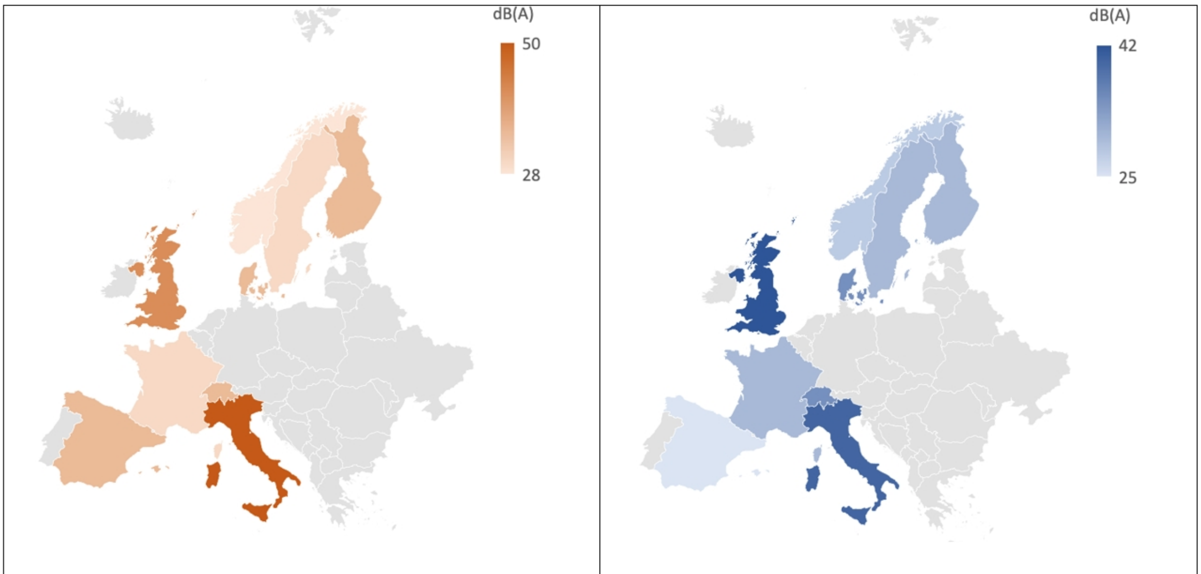
Different nations currently have different approaches. Not all nations divide the national territory into different areas, but even in the absence of areas (such as in France for example), there are still very restrictive limits, especially for the noise allowed inside homes.

The analysis shows that even when the approaches are similar, different methods of measurement are often adopted to determine the noise annoyance. This annoyance is then defined starting from different descriptive indices. An example concerning heat pumps is for example the penalty due to the identification of tonal sounds: this is foreseen in different countries, but each country has a different method for the calculation and application of this descriptor which in some cases heavily penalizes models of heat pumps for which the frequency of the compressor and its harmonics overlaps that produced by the rotation of the fan. But this does not happen with all descriptors used.

The national limits of the maximum permissible indoor noise level are given as a significant example of the results. They are summarized in a table and in a couple of simplified graphics

Topic	Building														
	EU Country											Other Country			
	FR	UK	AT	IT	ES	DE	PL	DK	SE	FI	N	CH	KO	JP	CN
There are Buildings acoustc insulation Laws?	Yes	Yes	Yes	Yes	Yes			Yes	Yes		Yes	Yes			
passive acoustic requirements of buildings	Yes	Yes	Yes	Yes	Yes	Yes		Yes	Yes		Yes	Yes			
Parameter used (insulation)	DnTw+C; L'nTw	DnTw+C; L'nTw	DnTw; L'nTw	R'w; L'nw; D2m,nT,w	DnTw+C; L'nTw	R'w; L'nw	R'w+C; L'nw	R'w; L'nw	R'w+C; L'nw+C		R'w; L'nw	DnTw+C; L'nTw+C			
Different requirement for terraced house and appartment			Yes			Yes						Yes (rent/property)			
Specific limit for HP or tetchnological services/installations in general				25 dB(A) or 35 dB(A)											
Parameters for services/installations				LAeq; LASmax											
Different limit for different indoor ambient				Yes											
Minimum indoor limit (day/night)	30 dB(A) (in the Rooms)	42 dB(A) (at window)		50/40 dB(A) (at window)	35/25 dB(A)			35 dB(A) At property edge	30 dB(A)	35/30 dB(A)	28 dB(A)	35 dB(A) (at window)			

Figure 1-2: *Synthesis Table [Sourcs: see D1.3]*



Building/indoor noise –minimum indoor noise admitted – Day period

Building/indoor noise –minimum indoor noise admitted – Night period

Figure 1-3: *Minimum indoor noise for day and night period [sources: see D1.3]*

Some requirements are very restrictive (28 dBA for Norway).

Here instead a brief summary of the European regulations on the noise of heat pumps and of the characteristics of the ECOLABEL is shown. The limitations on the sound power level present in the European regulations, which are very similar to each other, are compared with the requirements of the ECOLABEL. On the other hand, it is possible to see in the graph the limit sound power levels.

Attention: there is no total overlap between the products covered by the various regulations indicated. Despite this, it may be interesting to verify the differences in the requests expressed in terms of noise limits.

		European regulation on noise and ECOLABEL									
		Commission Regulation (EU) No 206/2012	Commission Delegated Regulation (EU) No 626/2011	Commission Regulation (EC) No 813/2013	Commission Regulation (EC) No 811/2013	Regulation n° 814/2013	Regulation n°812/2013	ECOLABEL			
Regards:		Ecodesign requirements for air conditioners and comfort fans	energy labelling of air conditioners	Ecodesign requirements for space heaters and combination heaters	labelling of products covered by regulation n° 813/2013	Ecodesign requirements for Heat pump water heaters	labelling of products covered by regulation n° 814/2013	EU Ecolabel for water-based heaters			
Applay to:		air conditioners below 12 kW		air-to-water and water(brine)-to- water heat pumps for space heating (so-called heat pump space heater) or for space heating and hot water production (so-called heat pump combination heater) with capacity not greater than 400 kW capacity not greater than 400 kW		air-to-water and water(brine)-to-water heat pump water heaters with a capacity not greater than 400 kW	air-to-water and water(brine)-to-water heat pump water heaters ... **limited to 70 kW rated capacity**		heat pump heaters equipped with external combustion and electrically-driven heat pumps	heat pump heaters equipped with internal combustion engine	cogeneration space heaters equipped with internal combustion engine
								PN or PE in kW	10+ 36 x log(PN+10)	30+20xlog(0,4xPN+15)	30+20xlog(PE+15)
LWA limits by rated capacity in dB(A)	0 - 6 kW	LWA = 60 dB(A) - indoor LWA = 65 dB(A) - outdoor		LWA = 60 dB(A) - indoor LWA = 65 dB(A) - indoor		LWA = 60 dB(A) - indoor LWA = 65 dB(A) - indoor		0 6	46,0 53,3	53,5 54,8	53,5 56,4
	6 - 12 kW	LWA = 65 dB(A) - indoor LWA = 70 dB(A) - outdoor		LWA = 65 dB(A) - indoor LWA = 70 dB(A) - outdoor		LWA = 65 dB(A) - indoor LWA = 70 dB(A) - outdoor		6 12	53,3 58,3	54,8 55,9	56,4 58,6
	12 - 30 kW			LWA = 70 dB(A) - indoor LWA = 78 dB(A) - outdoor		LWA = 70 dB(A) - indoor LWA = 78 dB(A) - outdoor		12 30	58,3 67,7	55,9 58,6	58,6 63,1
	30 - 70 kW			LWA = 80 dB(A) - indoor LWA = 88 dB(A) - outdoor		LWA = 80 dB(A) - indoor LWA = 88 dB(A) - outdoor		30 70	67,7 78,5	58,6 62,7	63,1 68,6

Figure 1-4: *Comparison between the European regulations on noise and the ECOLABEL [Sources: see D1.3]*

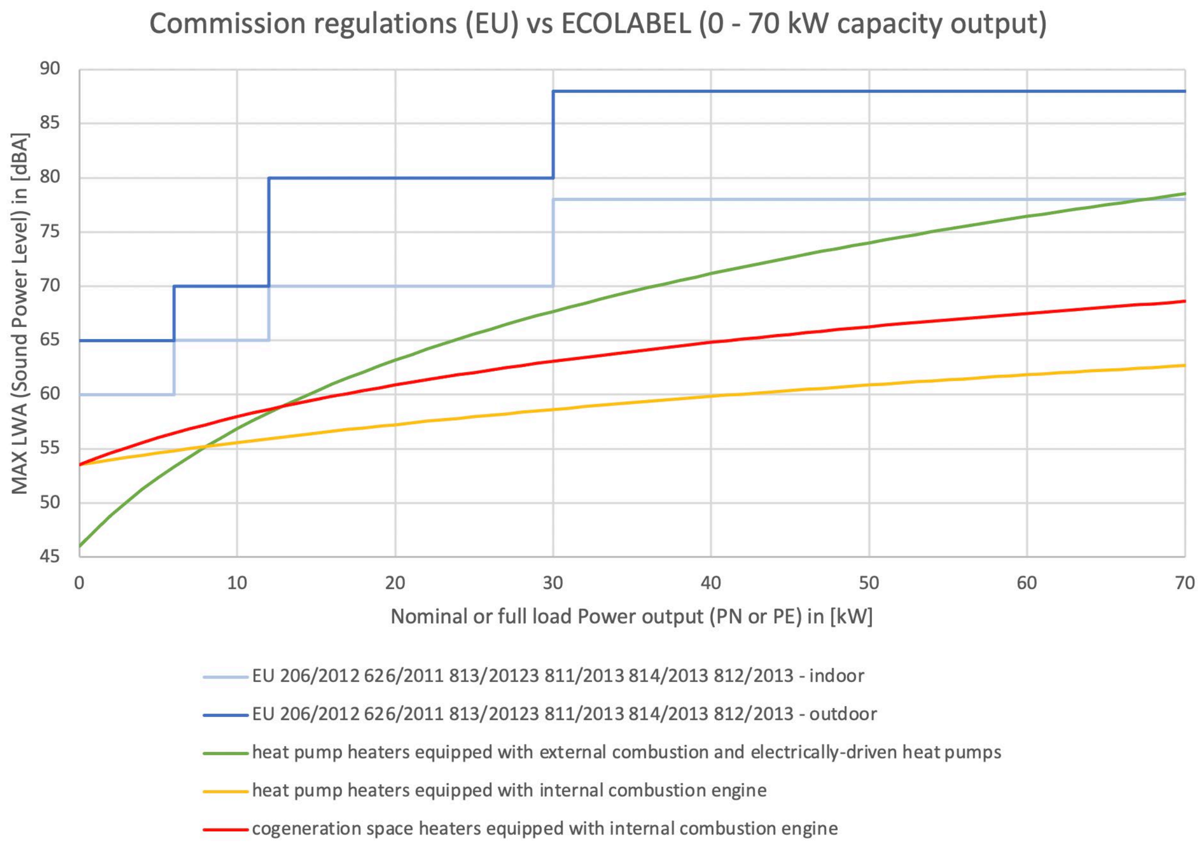


Figure 1-3: *Comparison between the European regulations on noise and the ECOLABEL [Sources: see D1.3]*

2. Task 2 "Report on Laboratory Tests on Air-to-Water Heat Pump and Heat Pump Water Heater"

Deliverable 2.1 – **Selection of Heat Pumps for Round Robin Tests** – Market figures – **IEA HPT Annex 51 D2.1**

2.1

Initially titled "Definition of heat pump units to be covered by the study" the task was heavily extended by covering the laboratory tests and analyzing the results. Therefore, the Deliverable 2.1 includes the market figures (see Table 2-1, 2-2 and 2-3), the selected units and considerations for establishing a test program.

Number of units	UE	AT	DE	DK	FR	IT	SE	Total
Air-to-water (Outdoor + exhaust)	277 712	12 076	45 800	3 773	74 595	26 960	23 413	**186 617**
water(brine)-to-water	86 076	4 479	18 350	2 248	2 199	762	22 843	**50 881**
Air-to-air (Outdoor + exhaust)	500 824	82	0	21 396	61 503	145 605	55 000	**283 586**
Heat pump water heaters (outdoor + exhaust)	124 844	5 556	12 450	40	80 753	2 944	0	**101 743**
Sub-total	989 456	22 193	76 600	27 457	219 050	176 271	101 256	**622 827**
Others	5 635							
Total	995 091							
Population (millions)	508	9	81	6	66	61	10	**232**

Table 2-1: *the European HP market in 2017 [Source: see D2.1]*

Nb units per 1000 inhabitants

Number units / Million inhab.	UE	AT	DE	DK	FR	IT	SE
Air-to-water (Outdoor + exhaust)	546	14.1	5.6	6.8	11.2	4.4	24.0
water(brine)-to-water	169	5.2	2.3	4.0	0.3	0.1	23.4
Air-to-air (Outdoor + exhaust)	985	0.1	0.0	38.5	9.3	23.9	56.4
Heat pump water heaters (outdoor + exhaust)	246	6.5	1.5	0.1	12.2	0.5	0.0
Total	1947	26	9	49	33	29	104

Table 2-2: *number of units sold per 1000 of inhabitants [Source: see D2.1]*

Market share	UE	AT	DE	DK	FR	IT	SE	Total	Annex 51/UE share
Air-to-water (Outdoor + exhaust)	28.1%	54%	60%	14%	34%	15%	23%	**30%**	67%
water(brine)-to-water	8.7%	20%	24%	8%	1%	0%	23%	**8%**	59%
Air-to-air (Outdoor + exhaust)	50.6%	0%	0%	78%	28%	83%	54%	**46%**	57%
Heat pump water heaters (outdoor + exhaust)	12.6%	25%	16%	0%	37%	2%	0%	**16%**	81%
Sub-total	100.0%	100%	100%	100%	100%	100%	100%	100%	63%
Population		4%	35%	2%	29%	26%	4%	**100%**	46%

Table 2-3: *the European HP market in 2017 in % for the countries of Annex 51 participants [Source: see D2.1]*

Table 2-3 shows the figures for the market share in EU and Annex 51 participating countries, highlighting the following points:

- Air-to-water units are widely used in the EU.
- HPWH are common in France, Austria and Germany
- Air-to-air units are widely used in Sweden and Denmark, but also in Italy maybe with reverse units for cooling
- Water-to-brine units are representing about 25% of the market share in Northern countries but less than 8% in the EU.

For the round robin tests (RRT) the following types of heat pumps have been:

- Air-to-water unit (RRT1)
- Air-to-air unit (RRT3)
- Heat pump water heater (RRT4)

Deliverable 2.2 – **Round Robin Tests – Air-to-Water Heat Pump** – Heat Pump Water Heater – **IEA HPT Annex 51 D2.2** 2.2

For the decarbonization of the heating and cooling of residential buildings, heat pumps are considered as an advantageous solution. But the sound level they produce can sometimes be considered as disturbing or annoying and are a real hurdle to their deployment.

In one hand, the regulation is an effective way to provide a fair framework. The labeling helps the user to know the associated sound levels. It also defines the identical operating points at which to carry out the tests. In the other hand, the test standards allow the use of units under controlled operating conditions to get reliable and comparable results. These test standards are written as precisely as possible, to avoid interpretations (which are still possible).

Task 2 of Annex 51 has 2 objectives:

- to compare the results obtained between laboratories to check, after comparison of the results, whether the test methods are clear or whether they need to be improved.

- to provide input data for other tasks of Annex 51.

Interlaboratory tests

The tests are carried out on 2 types of heat pumps: an air-to-water heat pump and a heat pump water heater (HPWH). The test standards for the purely acoustic part are respectively EN 12102-1 and -2. They give requirements on how to set up the machine and measure sound levels. The operating points can be varied.

The acoustic tests are carried out on the air-water heat pump with a focus on the outdoor unit (see Figure 2-1), containing the compressor and the fan which are the main noise sources. About ten operating points (see Table 2-4) are defined, with conditions of EN 14511 but also operating points of standard EN 14825 (points A to F), and finally the "acoustic" point described in Annex

A of EN 12102-1. A measurement protocol is also drawn up and supplied to laboratories to eliminate the simplest points of misunderstanding. The tests are carried out partially or completely by the 7 laboratories participating in Annex 51. On the most usual point of EN 14511 A7 (6) °C and W30-35 °C), the results compare well (see Figure 2-2) despite the wide variety of environments and measurement techniques. For some test points less usual for acoustic tests, some more important deviations could have been found without it being possible to analyze their origins, due to lack of sufficient data.

For the tests on the HPWH (see Figure 2-5), an inlet/outlet ducted unit on the outdoor air, the objective was mainly to perform standardized measurements according to the new standard EN 12102-2 (being published). Only a few laboratories were able to participate due to the complexity of the implementation of this device. Most of the results are consistent.

The results are often convergent, which is a positive indicator (see Figure 2-6). These deviations will be useful for the standardization committees to improve the drafting of standards, during revisions for example.

Input data

Taking advantage that the heat pump is being tested in laboratories, the usually untested configurations in acoustics (typically the operating conditions of EN 14825 for the "average" climate) provide additional information regarding the noise levels at various operating points (see Figure 2-3). The primary relationship between noise and fan rotational speed can be highlighted, followed in second order by compressor rotational speed.

Continuous acoustic measurements with a very short time step were made during the icing and defrosting phases (see Figure 2-4), showing that for positive temperatures, the icing led to an increase in noise of nearly 3 dB(A). In addition, the defrost is also described with precision, the different phases are clearly observable.

Directivity tests are also carried out with measurements all around the unit, showing differences of ± 3 dB depending on the measurement direction, these differences being important to be exploited when the sound levels radiated in the vicinity are to be calculated.

All these investigations deserve to be repeated on other types of machines to be able to confirm (or not) the observed trends.

RRT1 Programme : Measurement Points									
Nr.	**Standard**	**Condition**	**Air dry bulb (wet bulb) temperatures (°C)**	**Water inlet/outlet temperatures (°C)**	**Setting from manufacturer table**	**Set temperature**	**Fan**	**Mode**	**Liquid circulator setting**
1	EN 14511	standard rating	7(6)	30/35	1	30	Auto	Heat (Sun)	max.
2	EN14511	standard rating	7(6)	30/35	1	30	Auto	Heat (Sun)	2
3	EN 14511	standard rating at max frequency	7(6)	30/35	10	21	Auto	Heat (Sun)	max.
4	EN 14825	C	7(6)	*/27	12	29	Medium (3 bars)	Heat (Sun)	max.
5	EN12102-1 A.4	reaching the same capacity as test C	7(6)	30/35				Heat (Sun)	max.
6	EN 14825	D	12(11)	*/24	11	30	Medium (3 bars)	Heat (Sun)	max.
7	EN 14825	B	2(1)	*/30	13	28	Medium (3 bars)	Heat (Sun)	max.
8	EN 14825	A/F (Tbiv)	-7(-8)	*/34	14	27	Medium (3 bars)	Heat (Sun)	max.
9	EN 14825	A/F (Tbiv) and maximum frequency	-7(-8)	*/34				Heat (Sun)	max.
10	EN 14825	E (TOL)	-10(-11)	*/35	15	25	Medium (3 bars)	Heat (Sun)	max.

(*) The water flow rate determined from test # 1 shall be used with the indicated outlet water temperature

Table 2-4: *operating conditions of the RRT1 on the air-to-water unit [Source: see D2.2]*

Figure 2-1: *Installation of the unit in a double reverberant room [Source: see D2.2]*

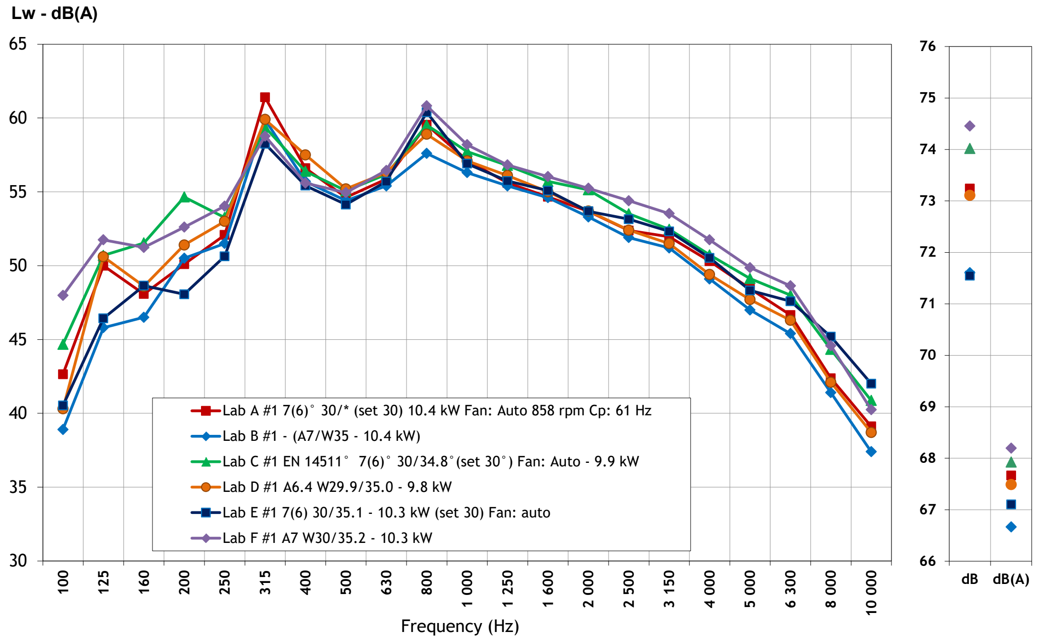


Figure 2-2: *sound power levels at EN 14511 operating condition (Test #1). It is encouraging to see that all laboratories find quite close results, despite the various acoustic methods used (Annex 1 for laboratories description). This shows their reliability/robustness of the acoustic test methods and their implementation by different laboratories. [Source: see D2.2]*

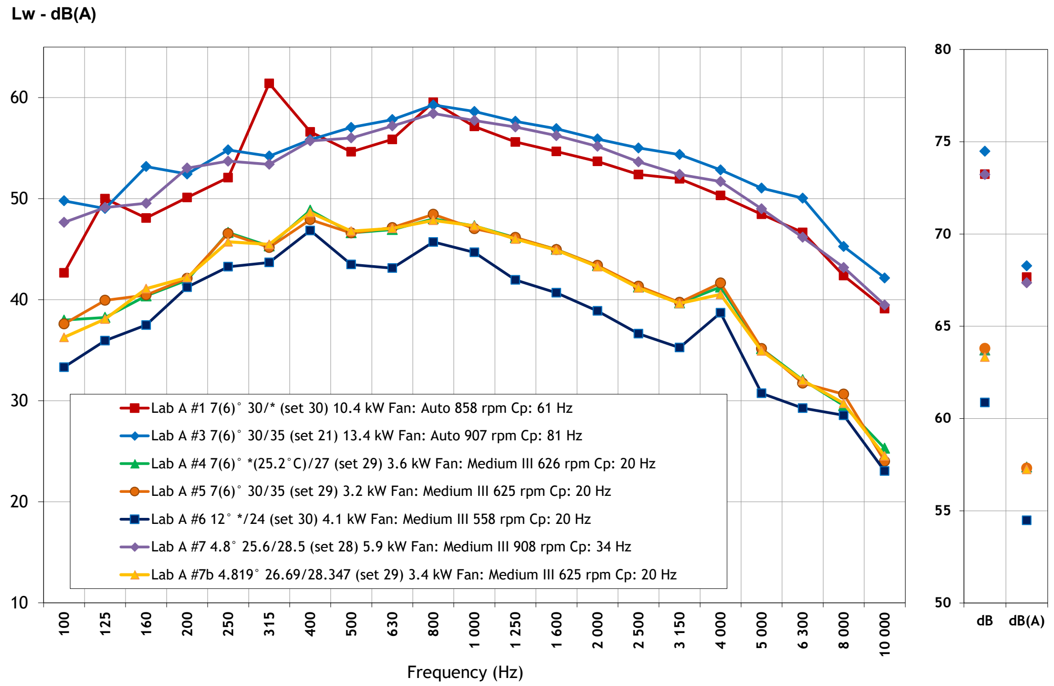


Figure 2-3: *influence of operating conditions on the sound level - different operating conditions lead as expected to variable sound power levels and different spectrum shapes. In the present case, the standard rating condition (configuration #1) exhibits a peak at 315 Hz band which disappears when the compressor and the fan are boosted at their maximum frequency; the modal coincidences do not exist anymore. In spite of an average difference of 1.5 to 2.5 dB over the spectrum, the overall value only differs by 0.8 dB(A), due to the peaks removal. [Source: see D2.2]*

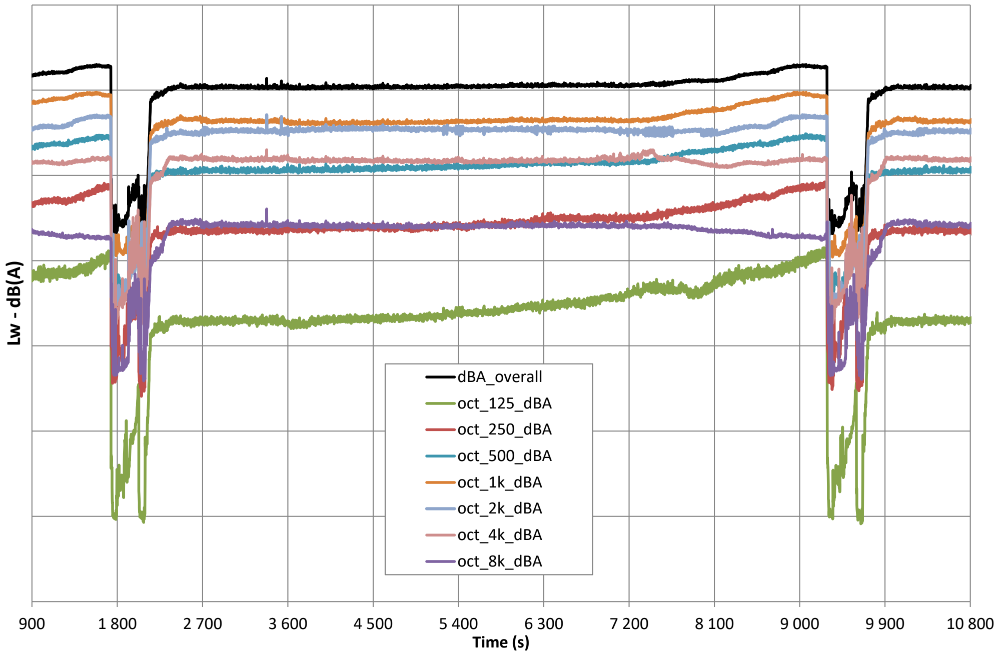


Figure 2-4: *Time dependent A-weighted sound power levels (in octave bands) between two defrosting phases configuration #3: EN 14511 frequency max [Source: see D2.2]*

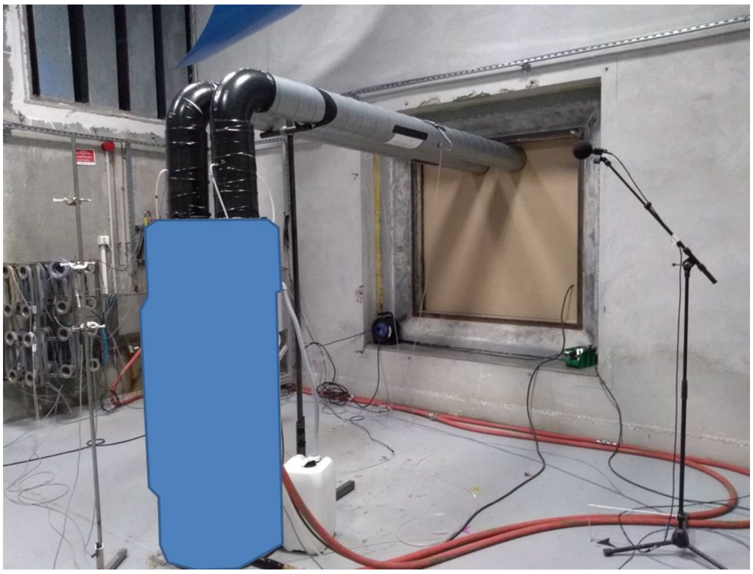


Figure 2-5: *Installation of the unit in radiated noise configuration in CETIAT [Source: see D2.2]*

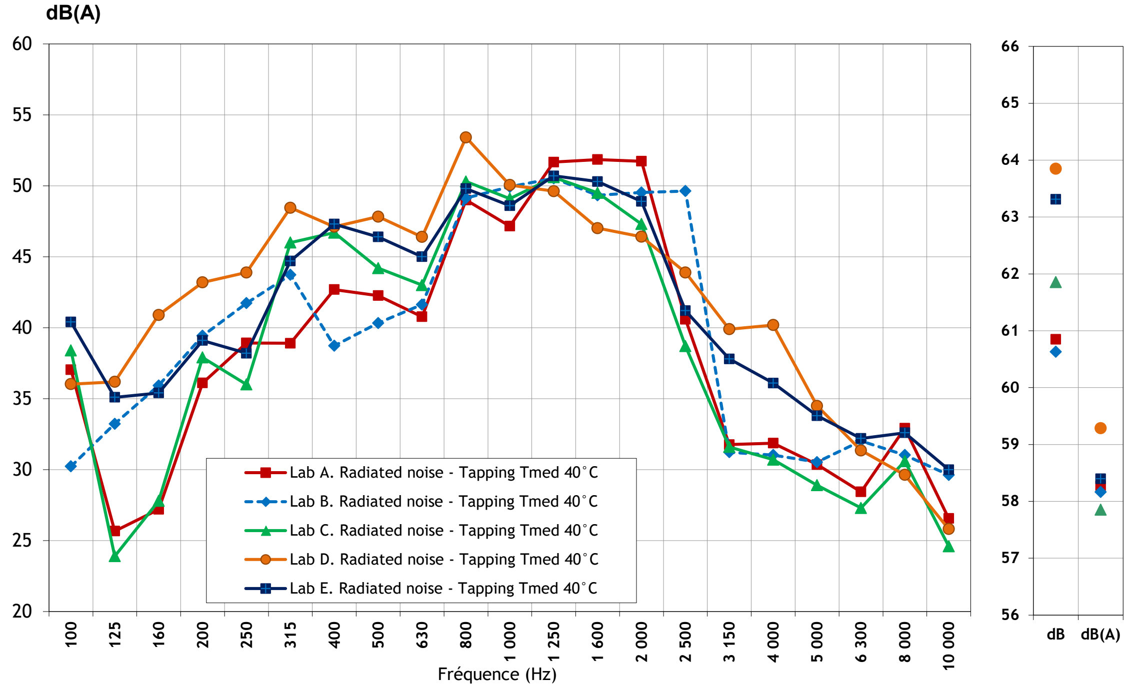


Figure 2-6: *radiated noise levels at Thw = 40 °C - These good results hide again some big local differences. Examples are given for labs A and C, which are very close for the major part of the spectrum except at 315/400 Hz and conversely at 1600/2000 Hz. [Source: see D2.2]*

Deliverable 2.3 – **Seasonal Sound Power Level** – Air-to-Water Heat Pump – **IEA HPT Annex 51 D2.3** *2.3*

For the first time, sound power levels of an outdoor unit heat pump has been determined for several operating conditions according to EN 14825 points A to E. In the same approach than for the SCOP calculation, a seasonal sound power level SL_w can be calculated, using the number of hours for each temperature of the average climate (see Figure 2-7) to weight each sound level for the overall average over the heating season.

The sound data measured at -7, 2, +7, +12 °C outdoor temperature are used, and for temperatures for which there are no acoustic results, a linear interpolation is applied to the acoustic values. Then a logarithmic weighted average is calculated, using the number of hours of operation for each bin of outdoor air temperature over the average climate, and the sound power level measured or interpolated at each bin temperature. The On/Off cycling above 12 °C and the defrosting cycle effects have also been taken into account, leading to a marginal decrease of the resulting overall sound power level .

As for any weighted average, the results are strongly impacted by the combination of the two main parameters, the number of hours and the associated sound level. A high sound level with only a few hours will not strongly contribute to the SL_w. With the logarithmic nature of the sound levels, the higher values are more dominant than for algebraic calculation, meaning that the lower sound levels will be less contributing.

From these calculations, a comparison can be done with the sound power level measured according to EN 12102-1 which is 6 to 7 dB(A) lower than the seasonal approach value , indicating that this EN 12102-1 operating condition may be not representative.

The EN 14511 standard rating condition 7(6) /30-35°C seems to be an interesting candidate condition as it gives quite close sound power levels, only 2 or 3 dB higher than the SL_W. This EN 14511 test condition is easy to implement. Moreover, it could avoid performing the tests according EN 14825 at different outdoor air conditions, those below 7 °C being difficult or impossible to maintain in acoustic test rooms. This EN 14511 standard rating condition seems to reflect a more representative acoustic behavior of the heat pump than the present EN 12102-1 Annex A.4.

A modification of the EN 12102-1 condition is desirable, both because it does not seem to be representative and because it is difficult to understand and implement in its current definition. The EN 14511 standard rating condition seems to be a good compromise (see Table 2-5) between accuracy/reliability of the test and representability of the sound power level of the heat pump over the heating season.

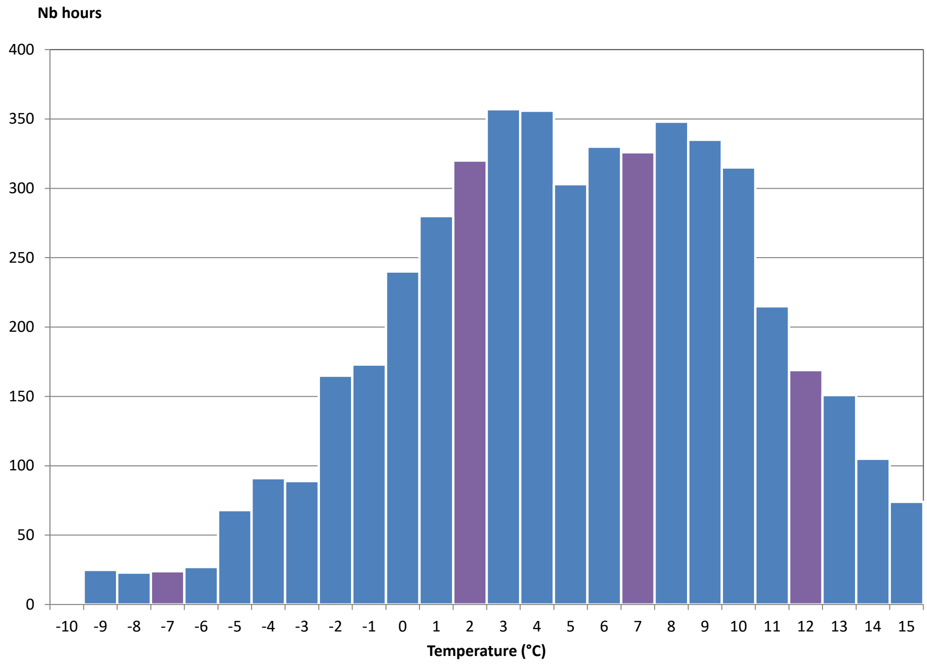


Figure 2-7: *number of hours for each step of temperature for average climate between –10 °C and +15 °C [Source: see D2.3]*

	Lab 1	Lab 2	Lab 3	Lab 4	Average
	Lw dB(A)	Lw dB(A)	Lw dB(A)	Lw dB(A)	Lw dB(A)
EN 14825 point A (-7 °C)	71.5	68.2	68.0	70.2	69.5
EN 14825 point B (2 °C)	68.9	67.2	68.1	68.6	68.2
EN 14825 point C (7 °C)	60.1	57.0	57.5	58.7	58.3
EN 14825 point D (12 °C)	58.1	54.4	55.1	56.3	56.0
Seasonal Lw dB(A)	66.0	63.7	64.3	65.3	64.8
EN 12102-1 "acoustics"	60.3	57.2	57.6	58.7	58.4
Difference	*-5.7*	*-6.4*	*-6.7*	*-6.6*	***-6.4***
EN 14511 A7(6) W30/35	68.2	67.1	67.5	68.0	67.7
Difference	*2.2*	*3.4*	*3.2*	*2.7*	**2.9**

Table 2-5: *input data and results for 4 laboratories (defrosting at ~ 55 dB(A)) [Source: see D2.3]*

3. Task 3 "Identification of noise at component and unit levels and noise control techniques"

Deliverable 3 – **Overview on Heat Pump Component Noise and Noise Control Techniques – IEA HPT Annex 51 D3** *3*

Heat pumps are more and more used in densely populated areas, which increases the need for quite heat pump design. The Task 3 report of the Annex 51 gives an overview on heat pump component noise and the fundamentals of noise control techniques. The aim of the report is to provide information and insights on the characteristics of different air and structure borne noise sources and an overview of various noise control measures, which can be applied in the design of quiet heat pumps.

First, the function and the working principle of heat pumps is explained briefly. This builds the basis for understanding why and how the different components of heat pumps generate noise. The main noise sources, the fan and the compressor, are discussed in more detail, but also secondary sources and transmission paths are addressed. The block diagram in Figure 3-1 shows how the noise sources can be divided into two groups: the primary or main noise sources, such as the fan and compressor, and the secondary sources, such as valves or heat exchangers, which occur due to the self-noise of the refrigerant and the air flowing through the system or the interaction between the compressor and the pipework and between the heat exchanger and the fan.

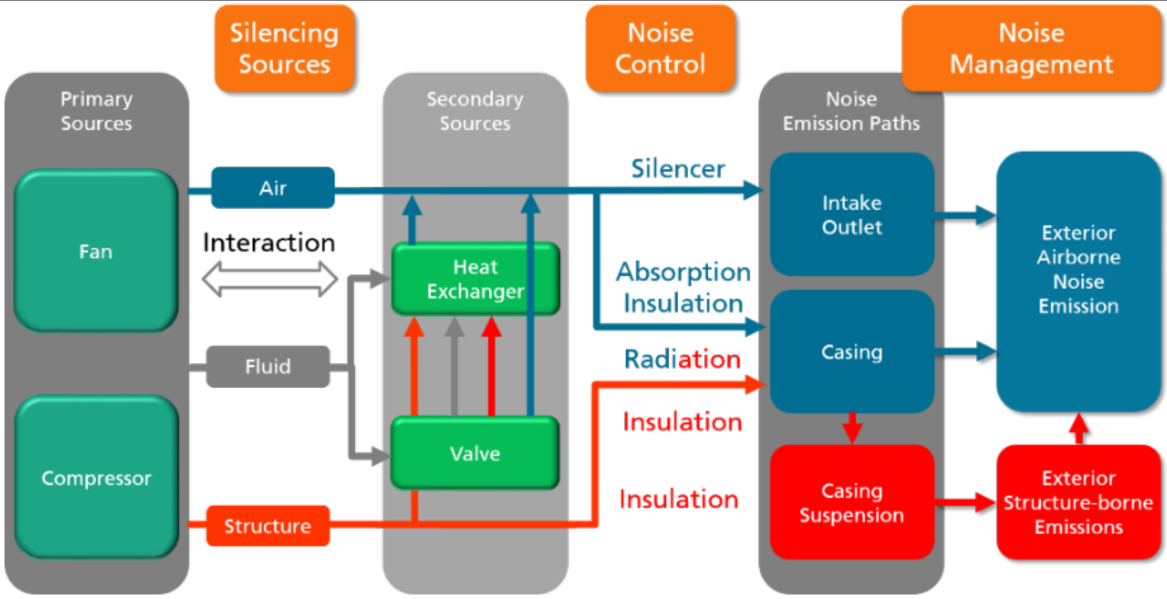


Figure 3-1: *Primary and secondary noise sources in a heat pump and main airborne and structure-borne transfer paths to the exterior. [Source: see D3]*

The most efficient method to reduce noise emissions is to suppress the noise generation at the source. In heat pumps, this can be achieved by using more quiet properly dimensioned compressors or fans. The next best way to reduce emissions is to decouple the main noise sources from the rest of the heat pump. For example, using elastic mounts to fasten the compressor to the heat pump frame can greatly reduce the vibrational power transmitted into the frame. Any source may transmit airborne or structure-borne noise via a number of different parallel paths. Hence, the further away from the sources, the more difficult it is to control noise transmissions efficiently. If noise control measures at the heat pump are not efficient enough, it may be necessary to protect the surrounding with additional expensive retrofit solutions such as noise barriers or acoustic housings.

The acoustic emissions of heat pumps can be influenced by many design parameters and varies greatly between various operation conditions. The report gives an overview on the principles of passive and active noise control from which specific noise control measures can be derived for different heat pump components and transmission paths. Any heat pump component may transmit airborne or structure borne noise via a number of different parallel paths. To reduce the noise emissions from heat pumps efficiently, all noise paths need to be treated according to their dominance and contribution. The noise emissions from fans for example, are dominated by aeroacoustics sources and can be reduced or modified by changing the fan blade geometry or by using flow grids to optimise flow conditions.

The fan is one of the two main noise sources of heat pumps and consists of broadband and tonal components. The control of broadband noise of axial and centrifugal fans is more complex than that of tonal noise. The main phenomena which contribute to the broadband noise are:

- Noise due to intake of turbulence,
- Blade trailing edge noise,
- Vortex shedding noise,
- Flow separation associated with rotating stall.

Noise due to turbulence, also called blade leading edge noise, is predominant when the flow entering the impeller is highly turbulent, e.g., in the cooling fan of a car with the radiator close to the fan inlet. Blade trailing edge noise may be reduced for instance by a serrated blade trailing edge, but this type of noise control is still the subject of laboratory research as the mechanisms associated with the serrations are not yet fully understood.

Measures to reduce fan noise can be an installation of a diffusor which minimises exit losses improves the fan efficiency. As shown in Figure 3-2, ebm-papst constructed an air inlet grilles for noise reduction. The "FlowGrid" is used to reduce the turbulence and to further reduce disturbances in the fan inflow.

a) b)

Figure 3-2: *Air-inlet grille for axial fans (a) and radial fans (b). [Source: see D3]*

Further, a relevant topic for heat pump manufacturers is the interaction between the fan and the heat exchanger and how they influence the acoustic behaviour of each other. Several parameters, such as the distance between the components or the angle of the heat exchanger, can have an influence on the fluid flow and on the aeroacoustic emissions. When the air enters the outdoor unit, the air immediately flows through the heat exchanger. The fins in combination with the refrigerant pipes or channels cause a turbulent flow field behind the heat exchanger (see Figure 3-3). The non-uniformity of the flow at the fan inlet due to turbulence is one of the main noise generation mechanisms in the flow domain.

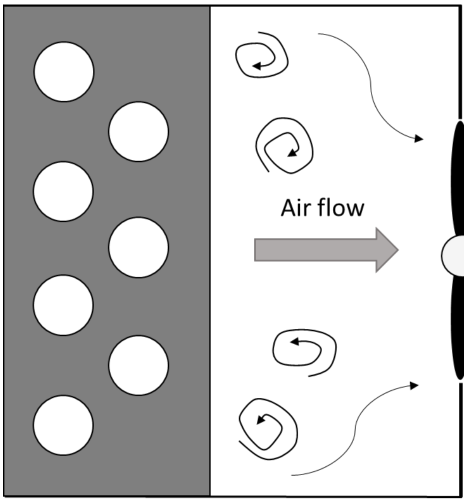


Figure 3-3: *Simplified flow field in a flow domain between the heat exchanger and the fan. [Source: see D3]*

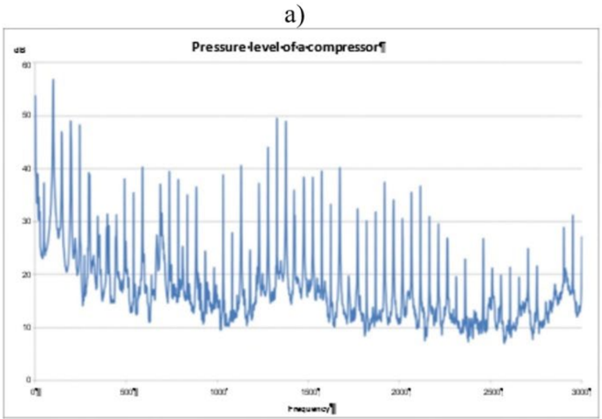
The compressor is the second main noise source of heat pumps, where they are used to compress the vaporised refrigerant. The vibro-acoustic of refrigeration compressors comprises several phenomena playing major roles, the origin of which is linked either to the dynamic behaviour or internal or external acoustics. The vibratory behaviour comes from two different aspects of motor behaviour: the first is linked to the movement of the motor itself, the second phenomena is linked to the projection of coolant against the upper part of the dome, located downstream of the compression chamber. The fluid thrown in this way, directly impacts the dome before it flows into the exhaust tube. This phenomenon is closely linked to the compressor drive frequency and the variations in the flow rate from the compression chamber. Very often, a sliding phenomena appears on the harmonics of the drive frequency due to the occurrence of resistive phenomena corresponding to the friction of the blades and the internal slowing of the compressor parts.

Several parameter influence the vibro-acoustic behaviour of compressors:

- Drive frequency: in the case of a variable speed compressor, the command frequency corresponds to the number of iterations made by the compression element during 1 second (rps). The harmonics of this drive frequency will appear in the vibro-acoustic spectrum of the compressor.
- Flow rate: linked to the compression/discharge phenomenon, the flow rate is a type of periodic excitation (corresponding to the speed of rotation in the case of a rotary compressor) which represents the phenomenon of expulsion of fluid towards the exhaust tube.
- Torque: linked to the rotation of the motor and the friction induced, this is a secondary contribution to the vibration and sound levels produced by the compressor.
- Pressure pulsation: the fluid ejected into the exhaust tube and circulating in the intake tube interferes harmonically (linked to drive frequency) with the tubes that radiate and vibrate as well as the compressor dome by repercussion.

For any type of compressor, the noise consists of a spectrum of lines and a broadband spectrum, as is the case with the majority of machines that have a motor element in regular movement (translation/rotation) (Figure 3-4). The vibro-acoustic of refrigeration compressors comprises several phenomena playing major roles, the origin of which is linked either to the dynamic behaviour or internal or external acoustics. These two sources have an impact on the elements which are firmly attached to the compressor: support structures and cooling pipes. **Fehler! Verweisquelle konnte nicht gefunden werden.** b shows exemplary a passive method to reduce radiated noise from the scroll compressor; the scroll compressor was surrounded by absorption material and a damping layer.

a)



b)

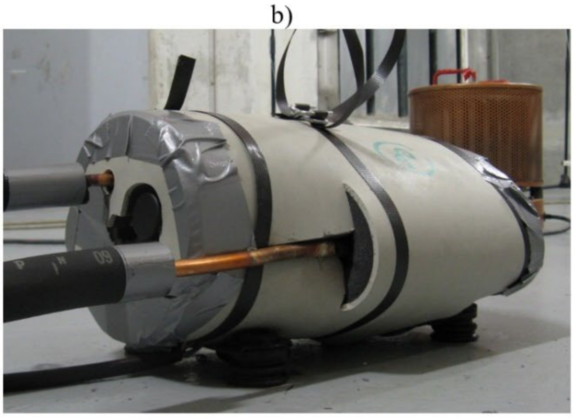


Figure 3-4: *Typical spectrum of SCROLL compressor noise a); application of absorption material and damping layer b). [Source: see D3]*

Noise can be subdivided in “airborne” and “structure borne noise”. **Airborne noise** refers to the sound that is transmitted through the air. A significant part of heat pump noise is emitted to the outside via openings, e.g., the air inlet on the suction side and the air outlet on the pressure side. There are various passive control techniques which can be applied on heat pumps to reduce the transmission and emission of airborne noise. In practice, there are three main airborne noise control techniques to reduce sound emission: sound absorption, sound insulation and sound attenuation. Figure 3-5 illustrates the principles of these three techniques, showing where and how they may be applied in machine acoustics.

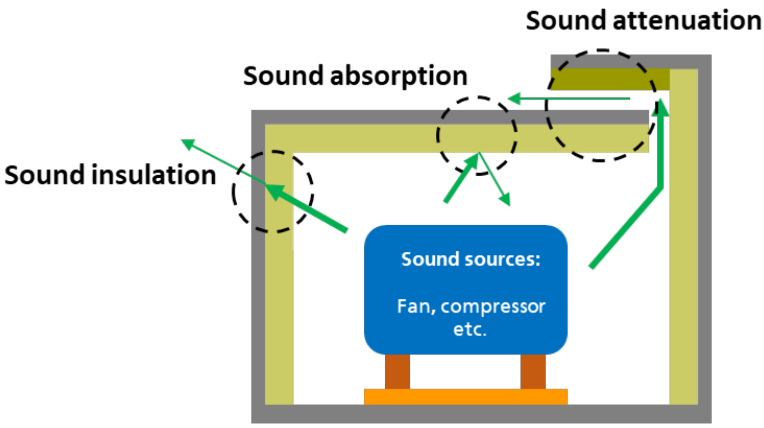


Figure 3-5: *Methods to influence the sound emission of a noise source, e.g. heat pump or motor. [Source: see D3]*

For **sound absorption,** absorbers, either in the form of porous material or so-called Helmholtz resonators withdraw acoustic energy from the incoming sound and reflect sound waves with less energy. When they are placed inside a machine casing, they reduce the sound pressure levels inside the casing. **Sound insulation** deals with the sound transmission from the inside of a casing to the outside via the closed casing surfaces. In contrast to sound absorbers, where the air molecules themselves can propagate into the absorber, acoustically sealed surfaces prevent the propagation of the air molecules. There are multiple parameters that effect the sound transmission through a partition, the most important one is the mass per unit area. However, damping and the stiffness also play an important role. **Sound attenuation** happens mostly in silencer systems placed in the inlet or exhaust channels. The working principle is close to the one of sound absorbers. Sound attenuation also withdraws energy from the sound, but in this case the sound passes the absorbers laterally. For the reduction of the overall sound emission, all relevant sound transmission paths need to be taken into account. Weak points in the sound insulation or inlet-outlet paths result in sound transmission paths which can dominate the overall sound emission.

Structure born noise, due to structure borne excitation by the compressor or the fan can be of great practical importance. On the one hand, the product designers have to think about the appearance of the casing, on the other hand, they have to consider the vibration properties of the material that is used. In the casing, vibration is generated through vibrating components, such as the compressor and the fan. Further, transmission paths, such as fluid pipes or structure parts, are the reason for noise transportation to the heat pump casing (see Figure 3-6). The vibration is transported through the heat pump pillars to the acoustic housing. The oscillations make the acoustic housing emit noise to the environment. Structure-born noise is also transported via additional transmission paths to the ground. As Figure 3-6 indicates, the base the heat pump is mounted to may also emit noise to the environment, which originally comes from the heat pump.

The noise emissions from compressors, may be dominated by direct sound radiation from the compressor casing, or via structure borne excitation of the heat pump casing. The direct sound radiation may be reduced by applying coverings made from dense, heavily damped material and sound absorbing materials. The structure borne noise can be reduced by using appropriate vibration isolation mounts. Structures which radiate sound through vibration are extremely diverse in their geometric forms, material properties and construction forms. In practice, the process of theoretical estimation of the detailed spectrum and directivity of the noise emissions is very difficult.

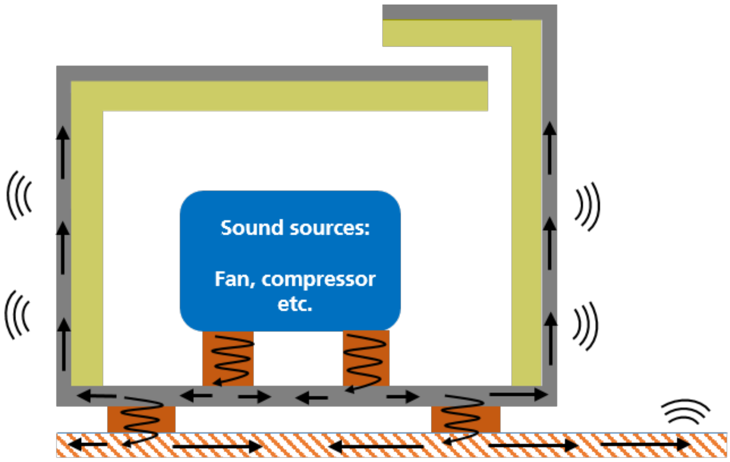


Figure 3-6: *Schematic drawing of the transmission of structure-borne noise from a vibrating heat pump to the environment. [Source: see D3]*

In the report, **active noise and vibration control** (ANC and AVC) techniques for treating airborne and structure borne noise are also briefly introduced. However, to date there are no off-the-shelf ANC or AVC solutions available for heat pumps. Towards low frequencies, the effectiveness of passive acoustic treatments is limited. According to the mass law mentioned in the section above, the sound transmission loss of partitions decreases with decreasing frequency. To be effective, porous acoustic absorbers should also have a thickness of about one quarter of the acoustic wavelength. Acoustic resonators e.g. Helmholtz resonators or λ/4 resonators, have a band-limited absorption characteristic, which depends on the tuning frequency and inner damping. The tuning frequency and efficiency of acoustic resonators largely depends on the resonator back volume. Hence, due to the long acoustic wavelength at low frequencies, conventional airborne noise control concepts are heavy and require a large installation space. For applications with weight restrictions and where the installation space is limited, active noise control (ANC) approaches can be an alternative. There are many different ANC concepts for various applications. In general, these approaches can be divided into two main classes, feedforward ANC and feedback ANC.

As a last resort, **retrofit solutions** such as noise barriers or encapsulations are addressed. Retrofit solutions may be required if the noise reduction measures applied to the heat pumps themselves do not meet the acoustic requirements. Typical retrofit solutions are so-called acoustic housings. Practical examples of such housings are illustrated in Figure 3-7. Such measures can be applied to already existing heat pumps or in noise sensitive situations where noise control measures at the heat pump itself are not efficient enough. In addition to noise reduction, these housings can protect heat pumps or air condition system from other environmental influences or vandalism.

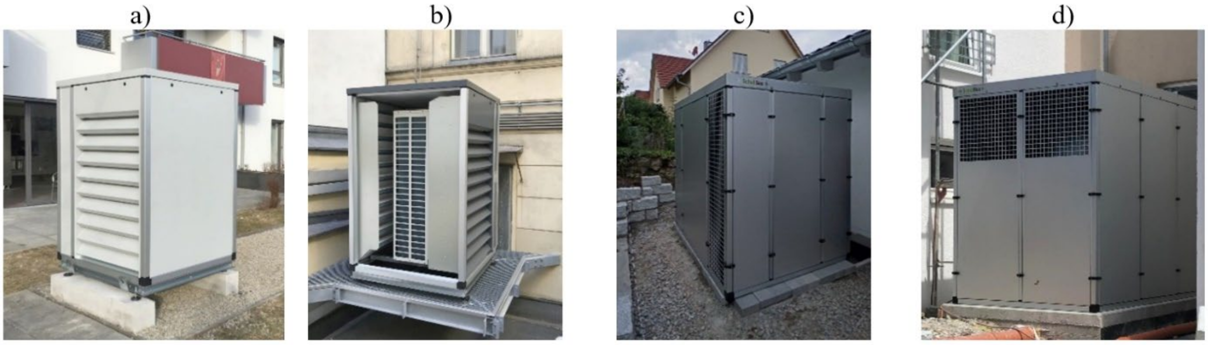


Figure 3-7: *a) and b) Retrofit Solution, Kellner Engineering GmbH, Austria; b) and c) Retrofit Solution, Schallbox dB(A) GmbH, Germany.*

4. Task 4 "Analysis of the effect of operating conditions of heat pumps on acoustic behaviour"

Deliverable 4 – **Analysis of the Effect of Operating Conditions of Heat Pumps on Acoustic Behaviour – IEA HPT Annex 51 D4** *4*

Heat pumps being identified as a key element in the long term decarbonization of the heating sector, understanding and improving their acoustical behaviour becomes crucial to ensure their widespread acceptance, especially in densely populated areas. To this effect and in conjunction with the content of other tasks, this task addresses three topics:

1. First, the coupling of energetic and acoustic heat pump models are reviewed (see Figure 4-1).
   Such approaches allow for an efficient and accurate evaluation of the dependency between states of operation and their resulting noise, including transient or cyclic evolutions like frosting. Thus, individual components can be sized accordingly, economically accounting for acoustics at early stages of development. Furthermore, the heat pump control strategies and operating envelopes can be adjusted through simulation (possibly in real time), in order to reach a combined optimization that best suits both energetic and acoustic needs.

2. Sound emissions during heat pump transient processes are identified and discussed. Those can be short-term events (seconds to hours), such as start-stop behavior of the compressor, load changes and inverter modulation, frosting/defrosting (in the case of air heat pumps, see Figure 4-2 to 4-5), hissing noise from the opening of the EEV (see Figure 4-6), domestic hot water tapping or other changes in external conditions. Some long-term phenomena (months to years) such as the ageing of grommets can also impact sound emissions.
   Even though transient noises prove to be quieter than steady noises near full capacity, they remain very relevant as they tend to draw more attention through their suddenness and possible evolutive or tonal character. Corresponding noise control measures are

further investigated within Task 3.

3. Finally, it is reported on the dependency of heat pump noise emissions on the type of heat source (see Figure 4-7), heat sink, the operating conditions/load levels and the control strategy (see Figure 4-8). Each of those influences are exemplified through experimental comparisons. Further results with a similar scope can be found in the Task 2 report.

A proper understanding of relations between heat pump types and sizes, their states of operation and their subsequent acoustic behaviour is essential to minimize noise disturbances. Pursued efforts in acoustical engineering, at component, unit and set-up levels, should pave the way for more comprehensive early stage design processes, including virtual prototyping and reliability engineering.

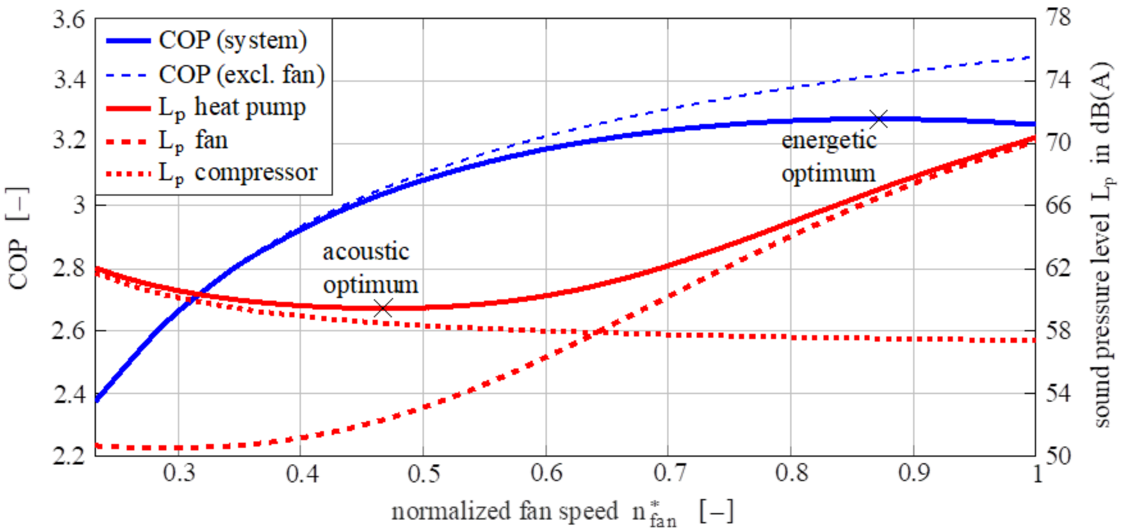


Figure 4-1: *Acoustic signatures of compressor and fan, as well as their sum as function of normalized fan speed, demonstrate the conflict between energetic optimal operating point and acoustic optimal operating point [Source: see D4]*

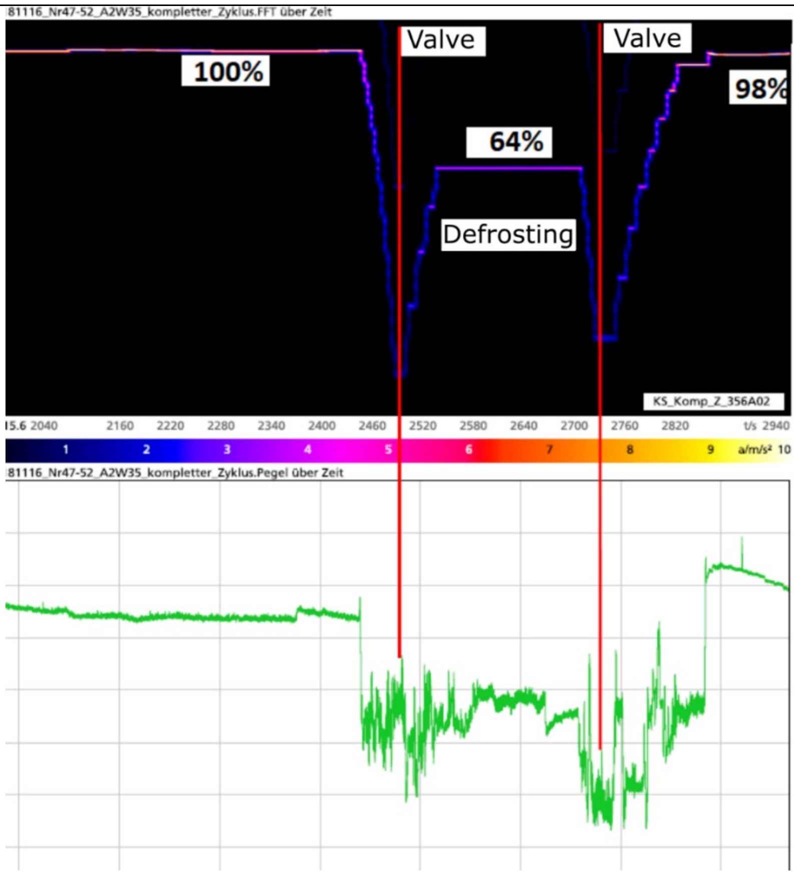


Figure 4-2: *Time evolution of a defrosting cycle, as measured at Fraunhofer ISE. The upper part shows the rotational speed of the compressor (acceleration sensor) and the lower part represents the global SPL, including brief events like the switchings of the 4-way valve. [Source: see D4]*

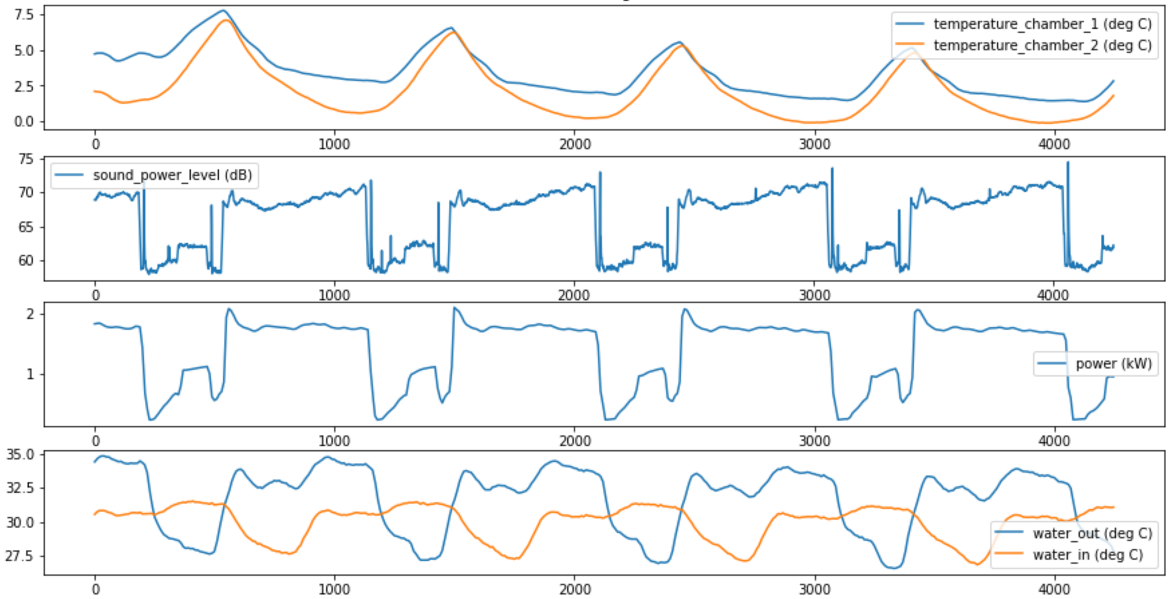


Figure 4-3: *Time history of important climatic chamber data. The defrosting cycles can be observed each 1000s or so, with a drop of the A-weighted sound power level. Short peaks are to be seen when the 4-way valve switches (source AIT).*

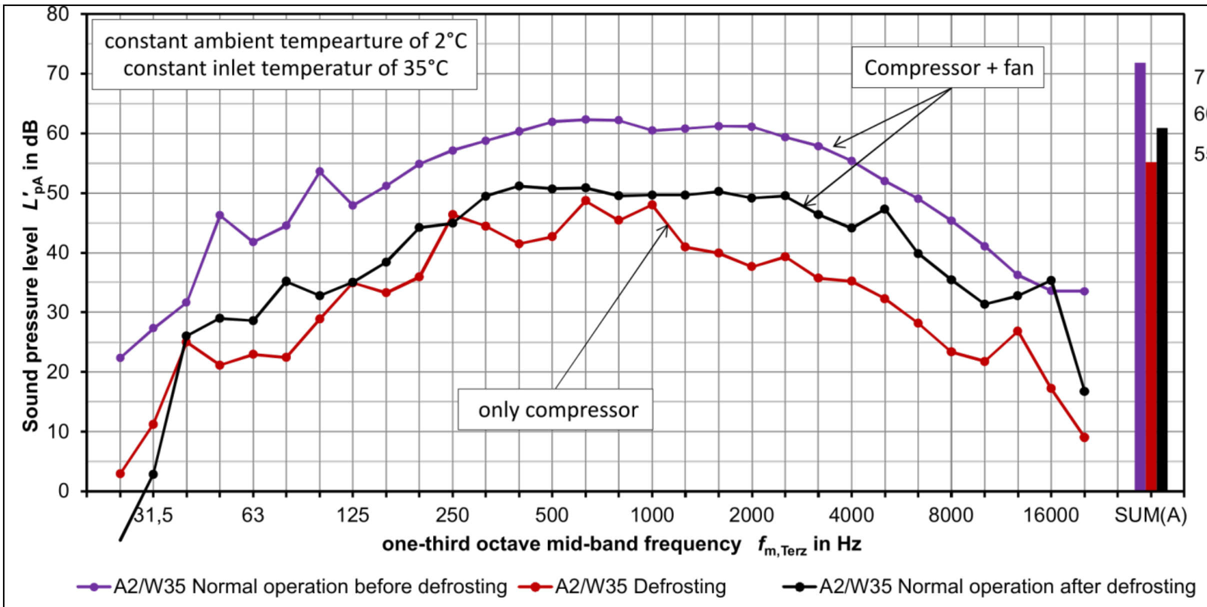


Figure 4-4: *SPL of a heat pump before (purple), during (red), and after (black) defrosting. [Source: see D4]*

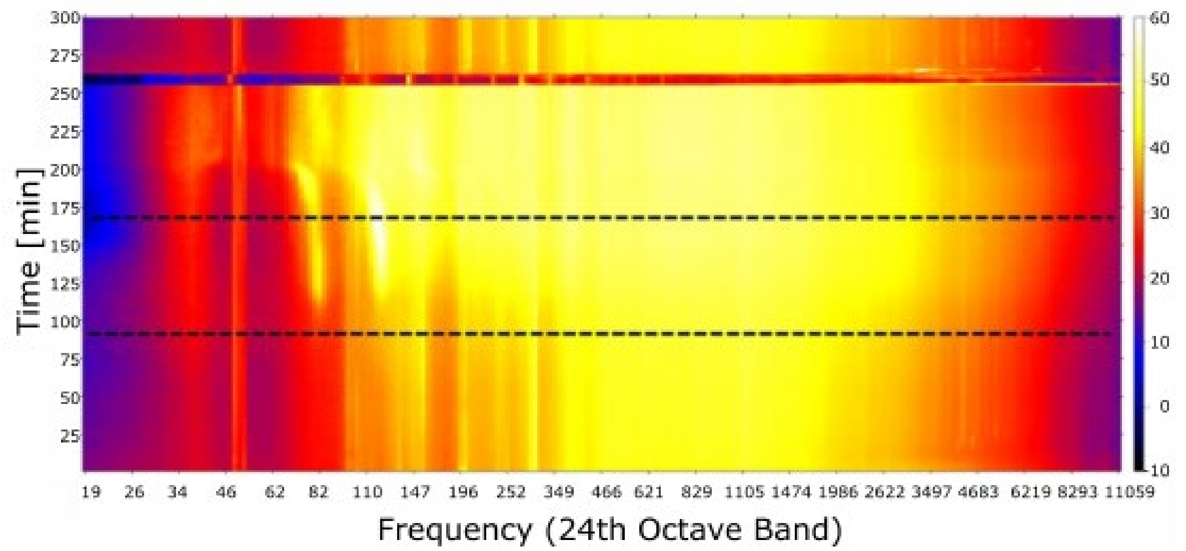


Figure 4-5: *Evolution of acoustic spectrum during frosting phase. The SPL increases of 8dB in the time between the 2 black lines [Source: see D4]*

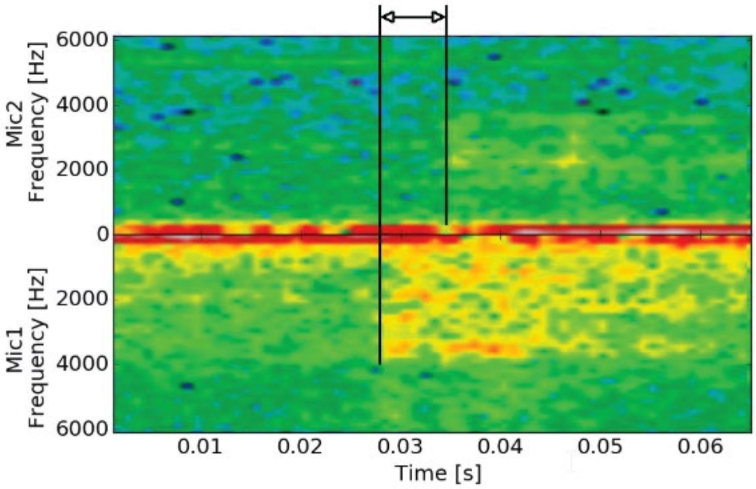


Figure 4-6: *Signature of the hissing noise from the opening of the EEV [Source: see D4]*

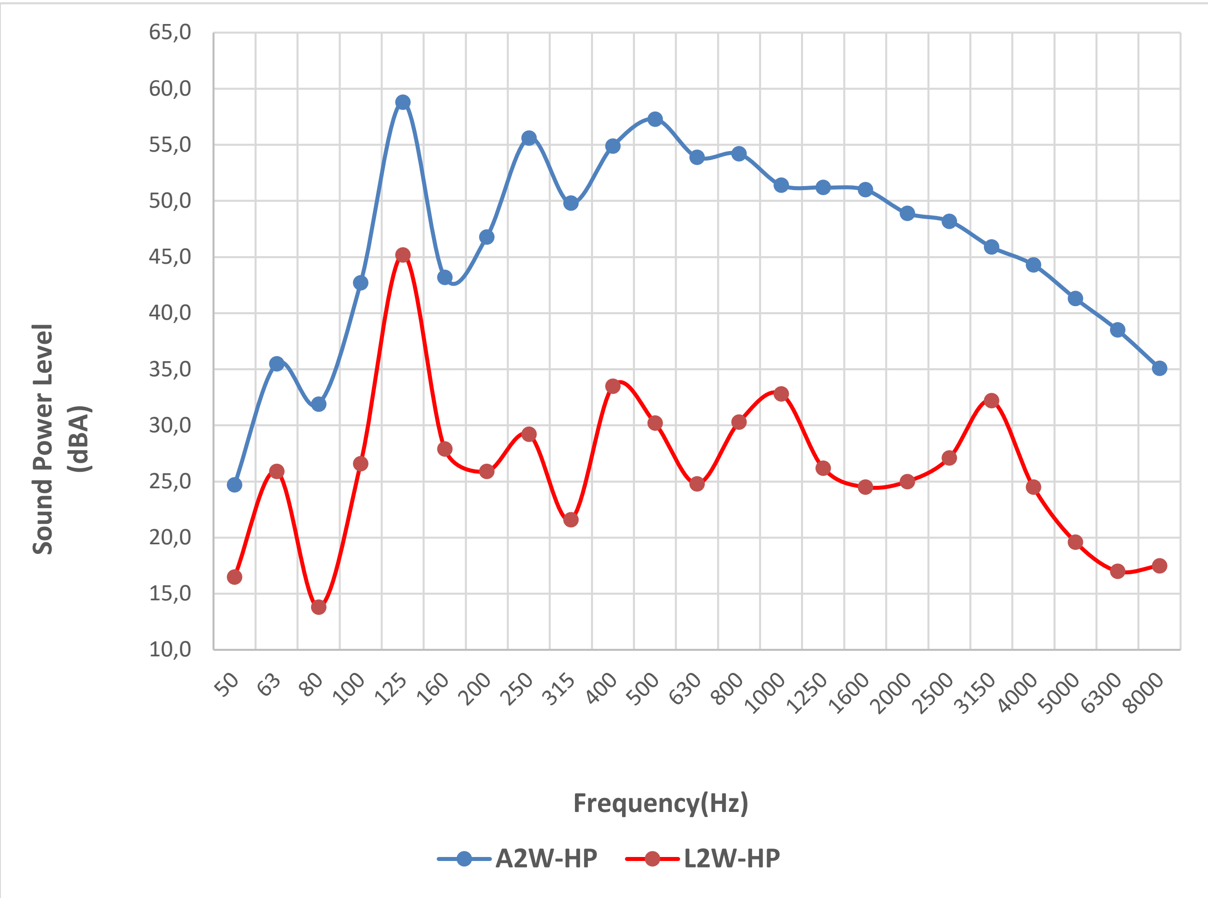


Figure 4-7: *Sound characteristics for an air source and a ground source heat pumps of similar capacity and at similar load. (source DTI)*

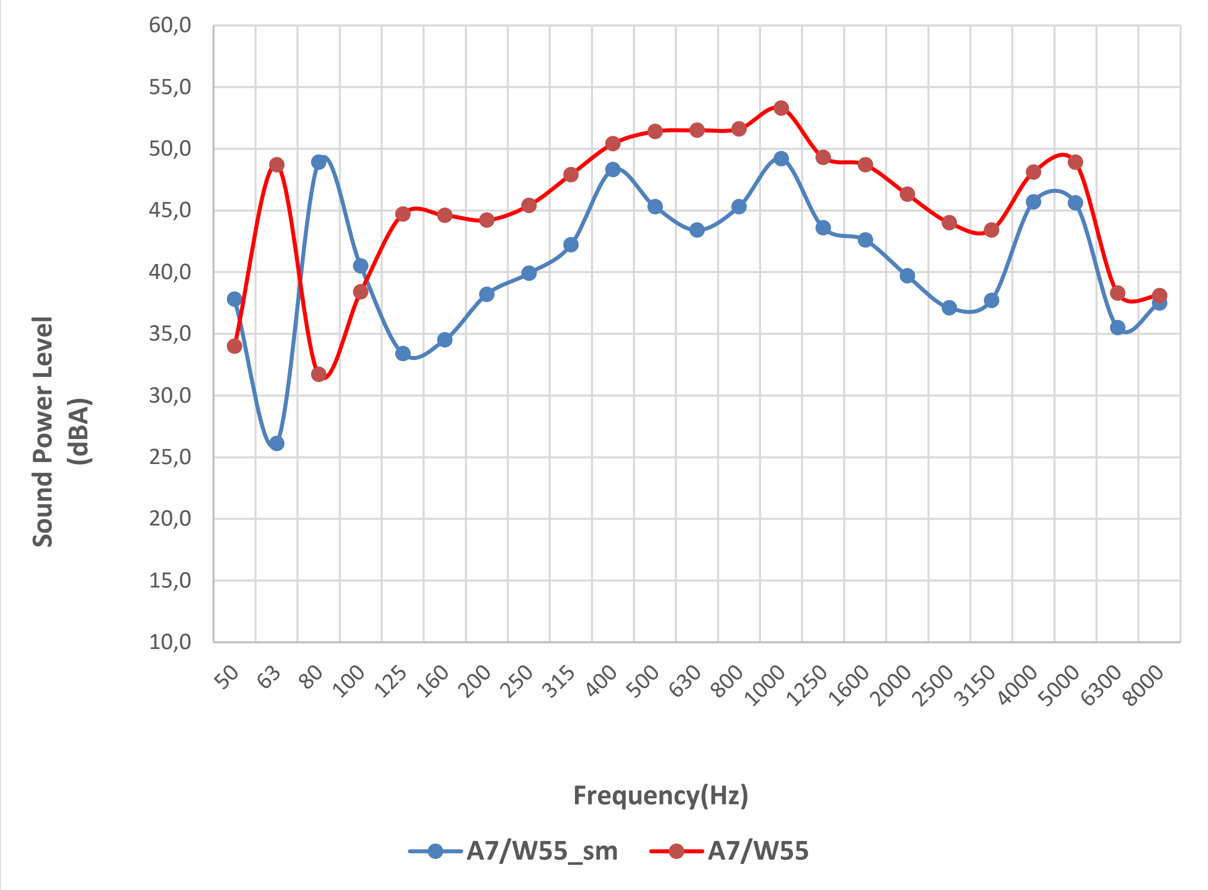


Figure 4-8: *Sound characteristics of an air-to-water heat pump for A7/W55 in silent mode versus normal A7/W55 operation. (source DTI)*

5. Task 5 "Heat pump installation and effects on surrounding environment"

Deliverable 5 – **Report on heat pump installation with special focus on acoustic impact – <u>IEA HPT Annex 51 D5</u>**	***5***
Air-to-water heat pumps are also often chosen where space is limited or where there are obstacles in the building regulations. Compared to air-to-air heat pumps, water, which is more suitable for this purpose, is used for heat transfer. A permit is not required. The disadvantage of the air-to-water heat pump is its comparatively low efficiency and increased noise emissions. The latter are mainly caused by the motor of the air intake fan and by the compressor. The aim of this work thesis is therefore to select and place air-to-water heat pumps in such a way that the sound pressure level in the surrounding houses is kept low. In the following chapters, light will be shed on several topics surrounding the placement of heat pumps. This report presents a selection of tools, which are used for calculating sound pressure levels. This includes simple formula based tools, which are often available online on websites of heat pump manufacturers or heat pump association. Examples shown include a Austrian (see Figure 5-1), German (see Figure 5-2) and Swiss (see Figure 5-3) version.	

Figure 5-1: *Main page of the Austrian "Schallrechner" [Wärmepumpe Austria, https://www.waermepumpe-austria.at/schallrechner (October 20, 2020)]*

Figure 5-2: *Main page of the German "Schallrechner" [Bundesverband Wärmepumpe e.V., https://www.waermepumpe.de/normen-technik/schallrechner/ (October 20, 2020)]*

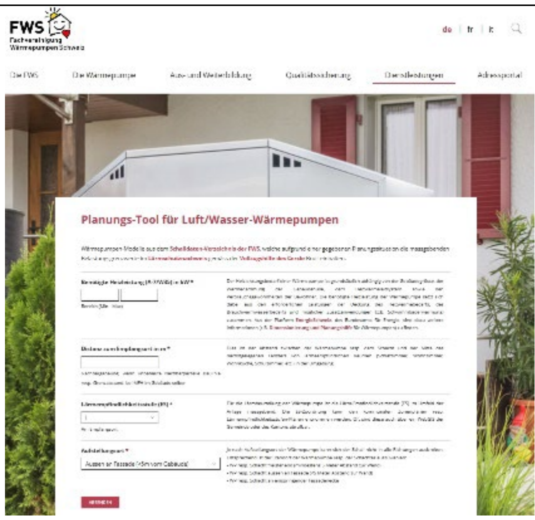


Figure 5-3: *Main page of Swiss "Schallrechner" [Website Fachvereinigung Wärmepumpen Schweiz https://www.fws.ch/fr/nos-services/outil-de-planification-pour-pompes-a-chaleur-air-eau/ (October 20, 2020)]*

Two-dimensional visualization is based on the same formulas, but allows the user to see the sound pressure levels in a horizontal plane surrounding the freely placeable heat pump (see Figure 5-4 and 5-5).

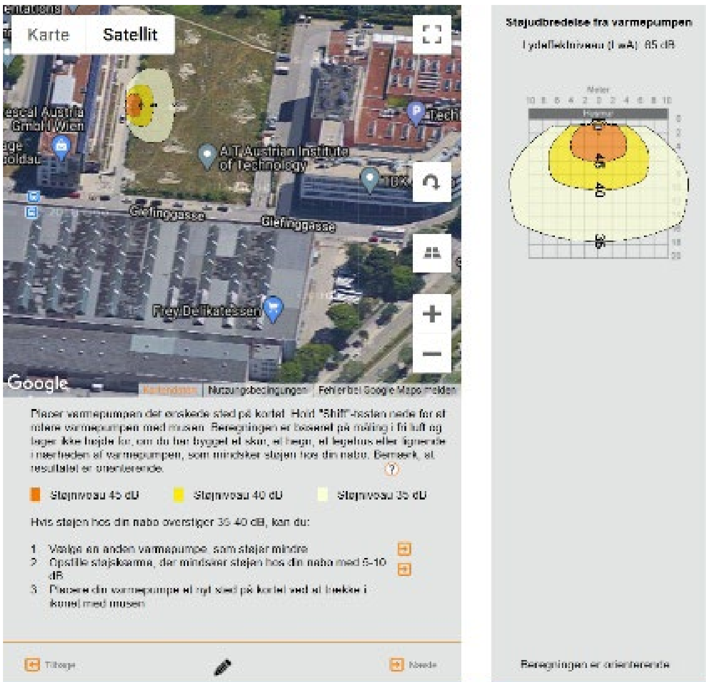


Figure 5-4: *Visualization of the sound power level of a heat pump using the "Heat Pump Sound Emission Calculator" of the Danish Energy Agency*

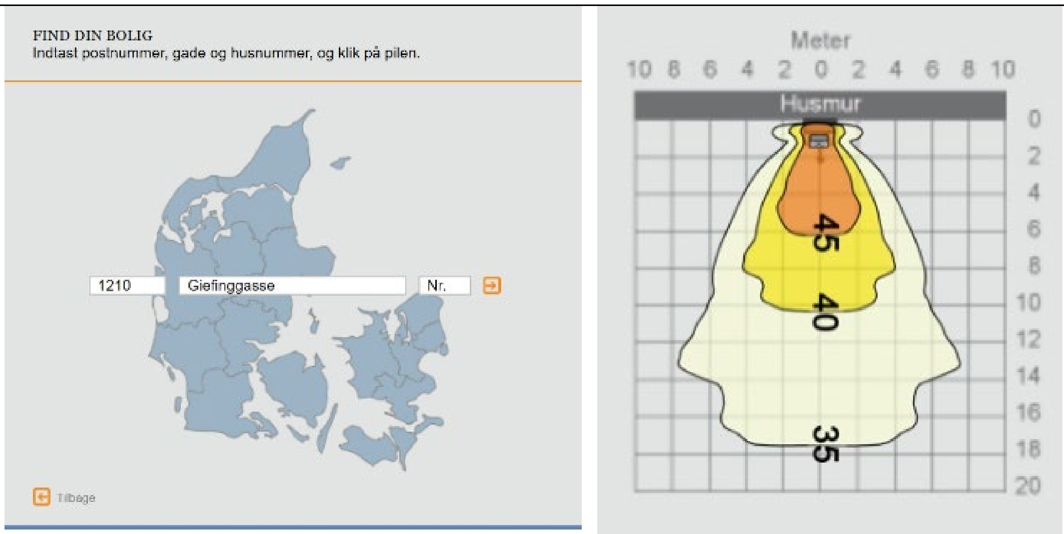


Figure 5-5: *(left) Selection of heat pump location [Source: Danish Energy Agency, (right) Sound propagation visualization depending on the nearby walls [Source: Danish Energy Agency, Denmark - http://stoejberegner.ens.dk]*

All these tools neglect - apart from the corner- and wall-placement "penalties" - absorbtion, reflection or frequency dependencies in the calculation. The underlying formula is very ease and can be calculated by hand. To include the effects of directivity and frequency behaviour as well as absorption and reflection a much larger computational effort would have to be made. Some approaches, which try to shed light on these effects are visited next. Advanced sound propagation tools like CadnaA, SoundPlan, NoiseD3D, Mithra-SIG, IMMI, Olive Tree Lab Suite and OpenPSTD are listed. The full three-dimensional calculation of sound propagation is of course possible solving the acoustic wave equation using e.g FEM and BEM.

The virtual placement of heat pumps using augmented reality is presented. This includes a description of acoustic measurements of noise sources (see Figure 5-6 and 5-8 left), the aurealisation approach (see Figure 5-7) and the methods for calculation sound propagation. The app (see Figure 5-8 right) is realized by a modeling and mapping approach and hardware and software for visualization and acoustics are described.

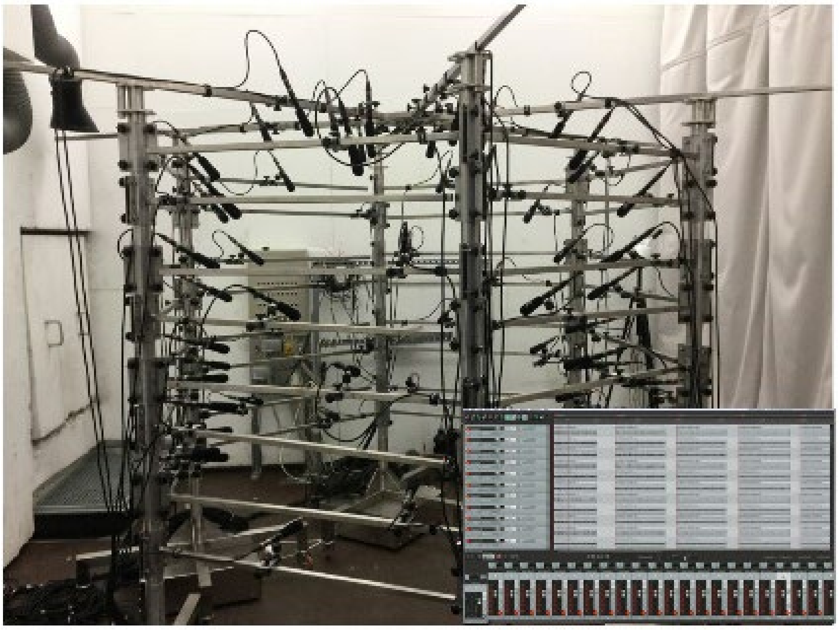


Figure 5-6: *Up op 64 microphones are placed around a sound emitting object forming an acoustic "dome". In this case a six-fold symmetrical setup has been constructed. The right lower part of the image shows the some of the wave-signals recorded during a typical test. [Source: see D5]*

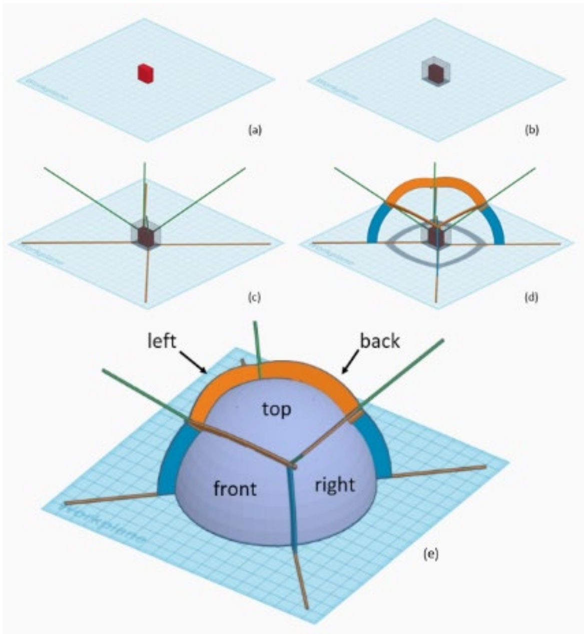


Figure 5-7: *: Visualization of the directivity aurealisation technique: (a) the red box represents the sound emitting HVAC component (e.g. heat pump); (b) the acoustic pressure is recorded in a specific distance to the emitting surfaces at 5 locations – a measurement surface is formed; (c) rays are generated connecting the emitter's corners with the corners of the measurement surface; (d) parts of the planes stretched by these rays intersected with a sphere; (e) final visualization of the 5 parts of the half-sphere attributed to the 5 microphone measurement positions. [Source: see D5]*

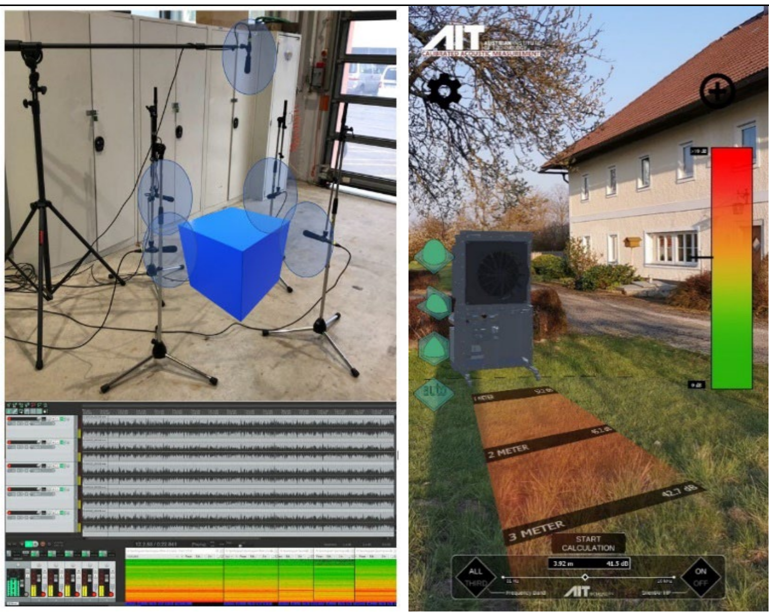


Figure 5-8: *(left) 5 microphones are placed around a sound emitting object, one at each side and one from the top. The lower part of the image shows the 5 five signals and their corresponding frequency content represented in waterfall images. (right) A laboratory heat pump (SilentAirHP) placed in a real environment using AR, with frequency dependent sound propagation. [Source: see D5]*

The acoustic interaction of multiple heat pumps including reduction measures is analysed using primarily the tool IMMI. First, the terraced housing estate chosen for a exemplary study is presented including the description of heating load, hot water provision, heating demand and the analysis of the neighbouring sites. The maximum sound propagation is calculated using IMMI following ÖNORM ISO 9613-2 and ÖNORM S 5021. Several scenarious have been compared: One heat pump per household (see Figure 5-9), one heat pump per house and a local heating supply scenario. In all cases heat pump selection and placement are outlined. Results are compared using a method introducing penalty points (see Figure 5-10) on all defined immission points (doors, windows, borders). For a promising case, calculations have been repeated introducing noise barriers into the calculation. Time of day dependent sound propagation (see Figure 5-11) has been visited to introduce user profiles of the different buildings. Alternative tools like OpenPSTD and Olive Tree Lab Suite and the involved options are described.

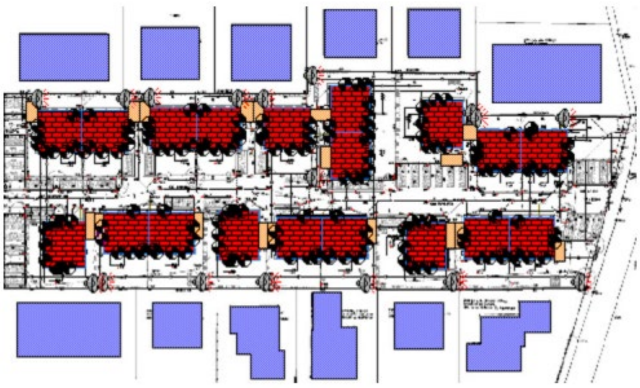


Figure 5-9: *Placement of heat pumps in one scenario. [Source: see D5]*

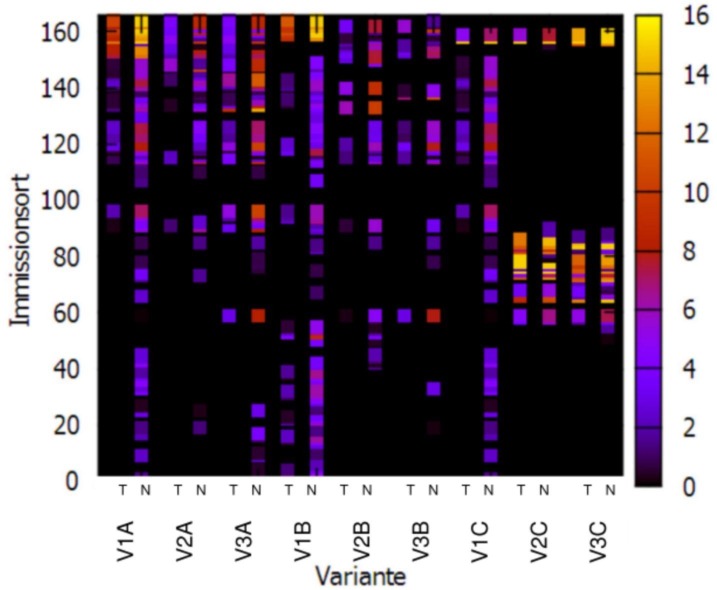


Figure 5-10: *Penalty points at the points of immission ("Immissionsort") for different variants and scenarios [Source: see D5]*

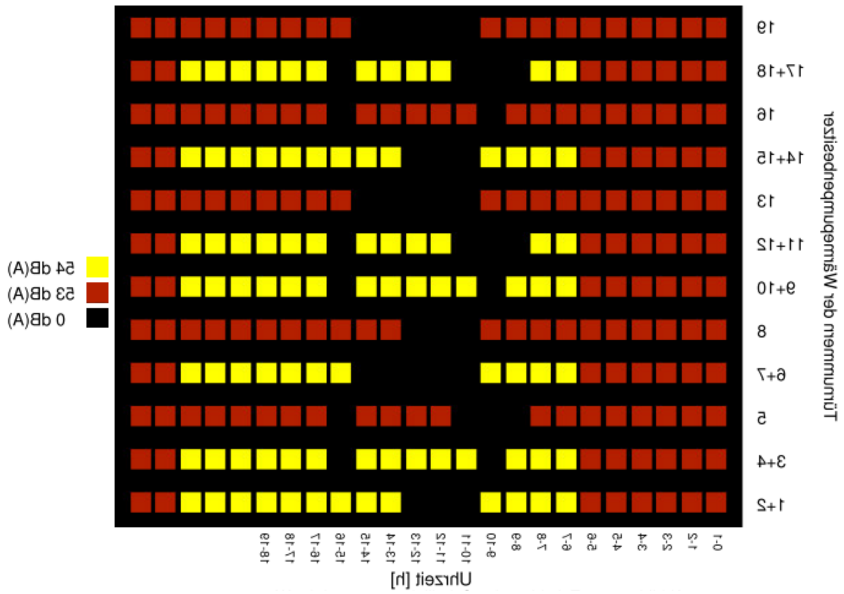
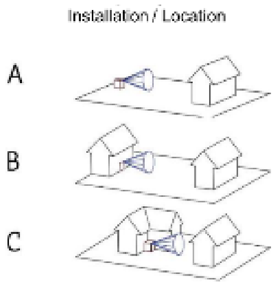


Figure 5-11: *Time dependent sound power level of heat pumps (the x-axis shows time of day, y-axis the different door numbers of the considered houses) [Source: see D5]*

The report additionaly is working on the analysis of unit placement, indoor & outdoor sound propagation. This includes the description of different installation locations (see Figure 5-12) and linked sound pressure maps (see Figure 5-13) showing the propagation of noise in various scenarious. A table summarizing the sound pressure level, which can be expected depending on the heat pump position (see Figure 5-14) is given.



Minimum distance to the neighborhood (without noise emission measures)			
Sound power level of the heat pump	Installation / Location		
	A	B	C
$L_{W,A}$ [dB]	Distance in m		
50	7	10	14
55	13	18	24
60	22	28	35
65	32	41	54
70	49	66	88

Calculated values according to ISO 9613-2

Figure 5-12: *Minimum distance to fulfil the 25 dB(A) target value (german version: Forum Schall (2013))*

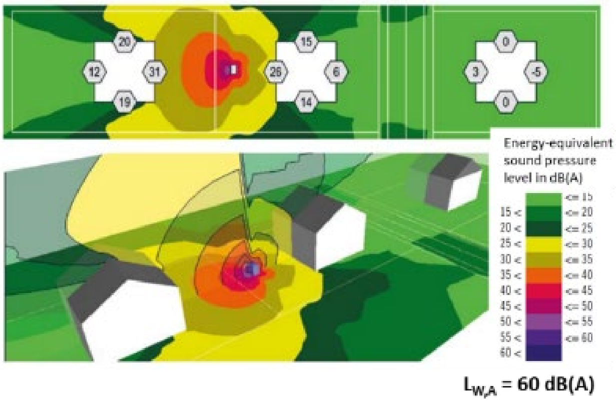


Figure 5-13: *Position close to the property line (Kopatsch and Doppler, 2014)*

No.	Description	Sound level in the neighborhood	Sound level at own building	
			Off the HP	Close to the HP
1	Position close to the property line	~ 30 dB	< 20 dB	> 25 dB
2	Position close to the property line with a protective wall	> 25 dB	< 20 dB	> 25 dB
3	Position close to the property line (90° rotated)	< 25 dB	< 25 dB	> 25 dB
4	Position close to the building	< 20 dB	< 25 dB	> 30 dB**
5	Towards the street	> 25 dB	< 20 dB	> 40 dB**
6	Rooftop installation	> 25 dB	< 20 dB	> 30 dB**
7	Tunnel installation	< 25 dB	< 20 dB	> 40 dB**

(green) Operation should be possible in most of the cases

(blue) For quite regions an optimization of the emission and / or the position could be necessary

(brown) A critical exceedance of the limits can not be corrected with simple measures. The chosen installation type should be reworked.

** The facades should not have any living or sleeping room

Figure 5-14: *Sound pressure level dependent on the heat pump position (LW,A = 60 dB) (german version: Kopatsch and Doppler, 2014)*

We outline the potentail of sound absorption at nearby surfaces and tabulates the reduction effects of various measures taken. Finally common unclever decisions in heat pump placement are visited such as wrong locations, roof installation, the (unforeseen) development of the neighbouring properties, the selection of improper sound absorbing measures and finally the installation of further units in the neighbourhood.

6. Task 6 "Heat pump installation and effects on surrounding environment"

Deliverable 6 – **Annoyance rating and psychoacoustical analysis of heat pump sound – <u>IEA HPT Annex 51 D6</u>**	***6***
Noise from heat pumps has a potential to cause annoyance of owners and neighbours, the degree of which is influenced by several factors. Factors like the acoustic characteristics of the noise, the installation and placements of the heat pump unit and individual's sensitivity to noise. To further increase the acceptance of heat pumps it is important to reduce this noise induced annoyance. In order to achieve this, detailed knowledge of how acoustic parameters influence the annoyance is necessary. Noise regulations are commonly focused on the A-weighted level, but other acoustic parameters may better explain the level of annoyance. These parameters could be the presence of low frequency noise and tonality, which the A-weighted level inefficiently assess. Common parameters used to assess the subjective perception of noise is loudness, sharpness, roughness, and tonality. These parameters have been developed to better explain the sensation of sounds. A way to assess the annoyance of noise sources is to perform listening tests. In this way it is possible to gain knowledge of the acoustic parameters that influence the annoyance. A possible drawback of these tests is that it often requires to use short sound stimuli, making it difficult to assess long term annoyance. A desired result is an annoyance index that show how different acoustic parameters explain the assessed annoyance response. Development of an annoyance index of heat pump noise could be beneficial when setting regulatory demands for heat pump noise. In task 6 of Annex 51, a listening test was performed on an Austrian and Swedish listening panel. Both panels were presented with the same set of sounds (see Table 6-1) and the same test set up (see Figure 6-1). The sounds investigated were recorded on the outdoor unit of an air-to-air heat pump at different operating conditions at different positions around the unit. All recordings were equalized to the same A-weighted level to investigate the effects of other parameters on perception. From the study a model of an annoyance index (see Figure 6-3 and Figure 6-4) was derived, which showed dependence on several parameters to have a sufficiently reliable model. The single best descriptor was roughness, but the model was improved by adding sharpness, loudness, and, to a minor degree, tonality. This shows that the perception of the heat pump noise is rather complex. Further, the sound rated as the most annoying was the condition with the lowest compressor speed. This condition also has the lowest fan speed, which also additionally might influence the perception. This report additionally present results from previous studies dealing with different aspects of heat pump noise. A Swedish study investigated the perception of noise from ground source heat pumps. The sounds investigated were recorded on three units at different compressor speeds. Sounds were again equalized for the A-weighted level. The results showed that the participants preferred sounds with higher compressor speed. The sound from the compressor is not surprisingly the dominant noise source due the absence of fan noise (compared to an air source heat pump). But the variation in acoustic characteristics due to the variation in compressor speed seem to be of importance.	

Setting	Compressor speed [Hz]	Fan speed [rpm]	Input power [kW]	A-weighted sound power level, L_{WA} [dB]
Low	34	610	0.78	52.7
Medium	48	770	1.09	56.5
High	73	770	1.76	59.1
Super high	79	770	1.9	58.2
Emergency *	58	770	1.28	57.6

Table 6-1: *List of recorded heat pump settings including fan and compressor speed and the measured A-weighted sound power level (according to ISO 3744). [Source: see D6]*

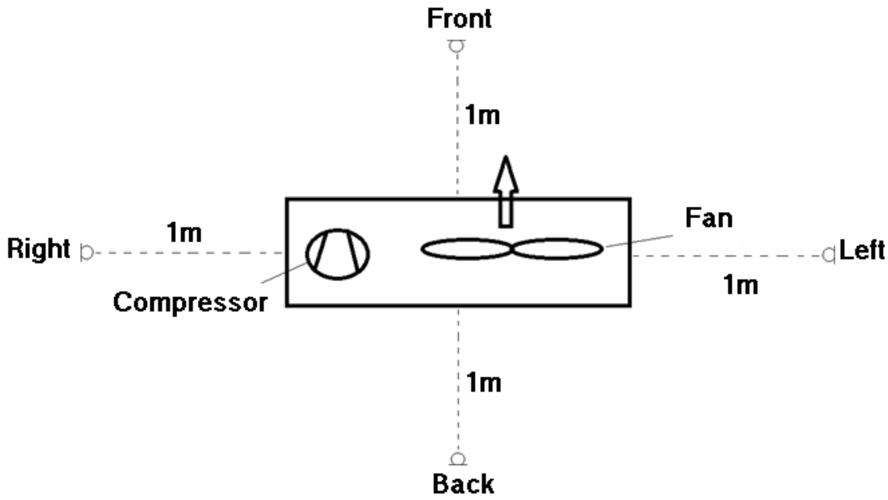


Figure 6-1: *Microphone setup for acoustic measurements. [Source: see D6]*

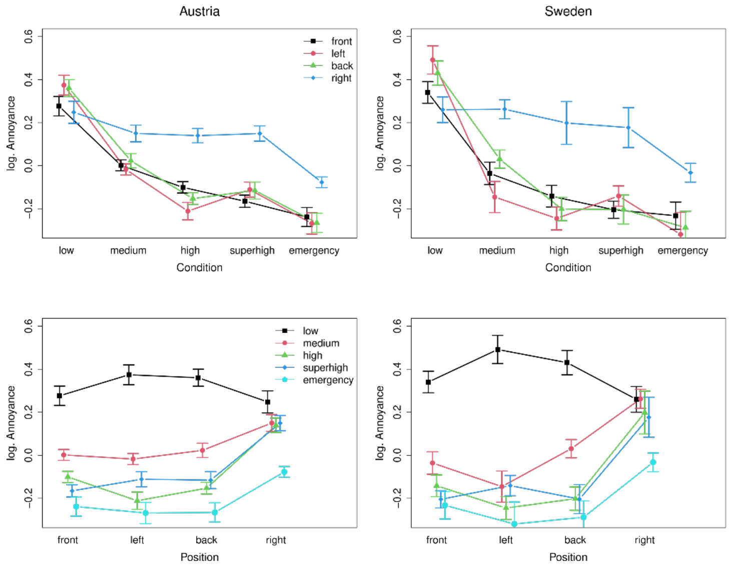


Figure 6-2: *Acoustic descriptors as a function of position. Operating condition is shown as different colors. [Source: see D6]*

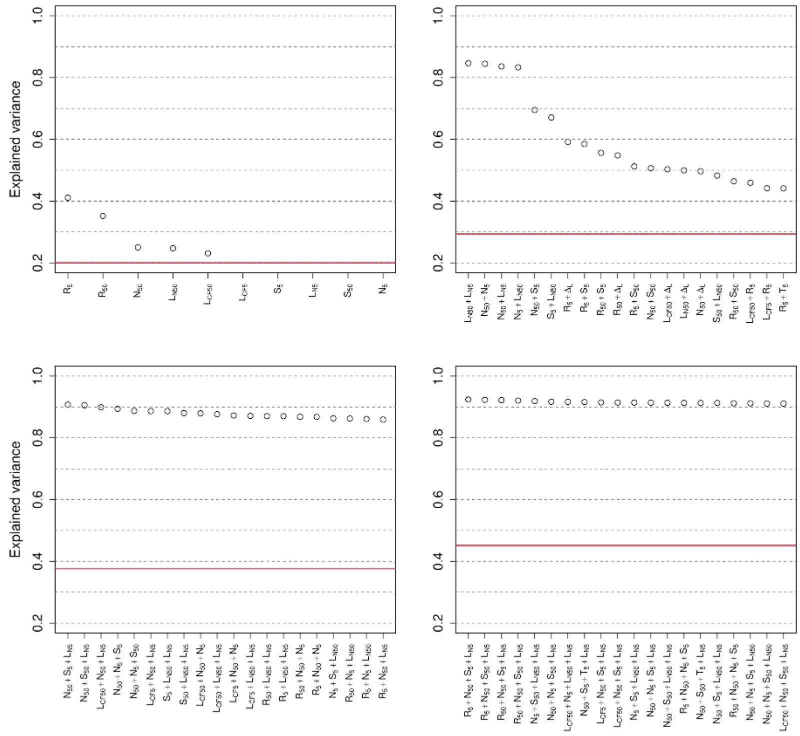


Figure 6-3: *Best models for combinations of up to 4 acoustical parameters. The red line indicates the 95% value for the explained variance if purely random parameters were used. [Source: see D6]*

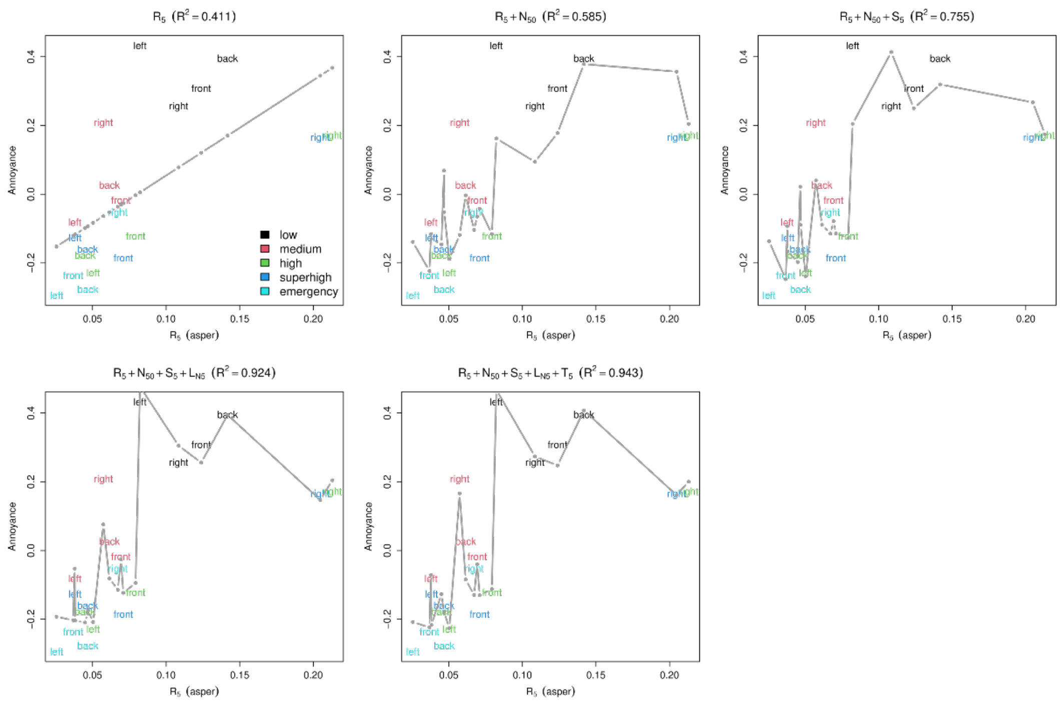


Figure 6-4: *Step-wise parameter addition. The response is plotted vs. the single best descriptor. [Source: see D6]*

An Austrian study investigated the effects of different noise mitigation measures on perception. Recordings were done in a climate chamber with absorbing walls and a reflecting ground. In this experiment the sound samples were not equalized. Acoustic data showed a considerable directionality of the different measures (see Figre 6-5) which was also present in the perception data. As a consequence, no overall effect of the measures (see Figure 6-6) was observed although there were effects depending on the emission direction. Interestingly, the A-weighted level was the variable which best explained the perception data whereas loudness explained less variance. Combining different variables, the best model contained A-level, loudness, and loudness level as well as sharpness and roughness with the latter four explaining an additional 10% of the variance.

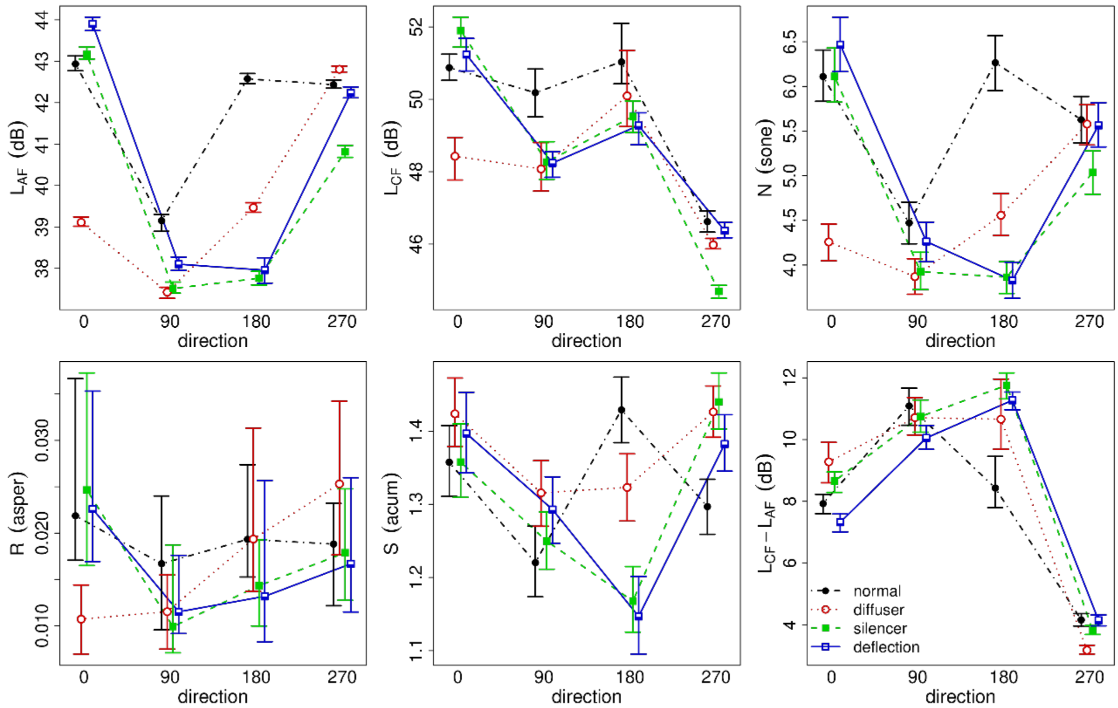


Figure 6-5: *Acoustical and psychoacoustical parameters as a function of direction and variant [Source: see D6]*

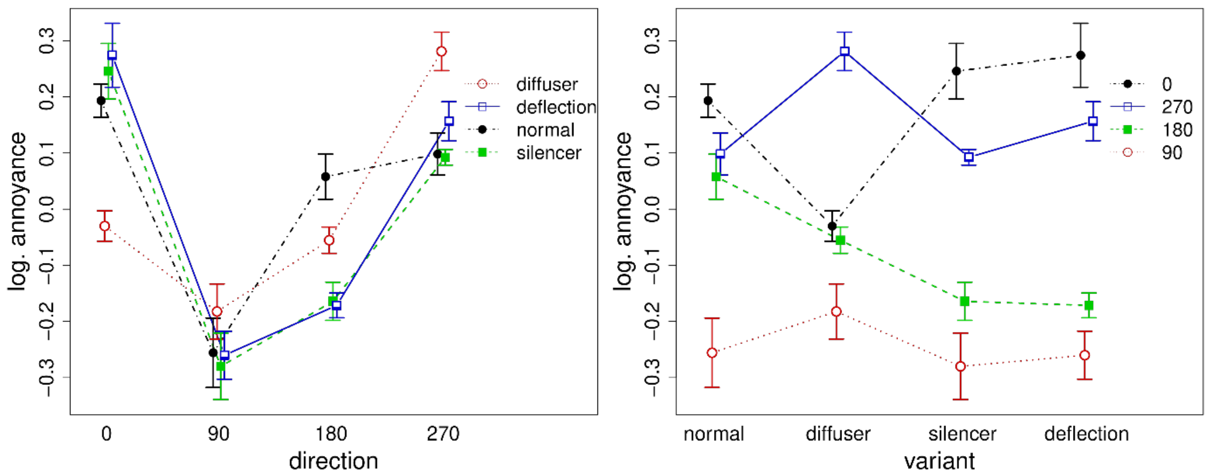


Figure 6-6: *Logarithmic annoyance as a function of direction and variant [Source: see D6]*

Overall, the results show that, in addition to the A-weighted level other acoustical parameters such as loudness, roughness, and sharpness may help to better model the perception of heat pump noise. Furthermore, the directional effects observed indicate, that the placement of heat pumps could have a relevant effect on how annoying people perceive the unit.	

7. Task 7 "Heat pump installation and effects on surrounding environment"

Deliverable 7.1 – **Educational material on acoustics of heat pumps** – **IEA HPT Annex 51 D7.1**	*7.1*
In the 7.1 deliverable document "D7.1 Educational material on acoustics of heat pumps" four guides are included: - Control the noise – a guide for installing air for water heat pumps - Heat pumps & environment acoustics - Heat pumps & recommendations for installation - Heat pumps - study of the risk of noise pollution in the vicinity The first guide is based on a documentation produced for the Danish Energy Agency. The three consecutive documents are based on fiche technquies from AFPAC, the French heat pump association. The original documents are available on the Annex 51 Website https://heatpumpingtechnologies.org/annex51/. **Control the noise – a guide for installing air for water heat pumps** covers an introduction to heat pumps discussing noise/sound authority, noise from air to water heat pumps (noise creation, noise measurement, influence of operation conditions, noise regulations), noise distribution (outdoor noise, indoor noise), calculation models (noise data, operating conditions, sound calculation tool), noise reduction, good installation (vibration sources and distribution cannels, rules of thumb regarding vibration isolation), control measurements, npise reduction (noise shields, noise gates, cabinet vibrations, cabinet noise) and examples (unappropriate placement, good and bad placements, control measurment of noise). **Heat pumps & environment acoustics** covers definitions of sound power and sound pressure, the calculation method of adding sound sources, recommendations for the implementations (location, reflection of emitted noise, reflection of received noise, directivity of ventilations, distance to property lines, installation under windows), reminder on the regulation of neighbourhood noise, application examples and emergence calculation (outdoor measurement, measurement inside buildings. **Heat pumps & recommendations for installation** covers supports (concrete base, metal frame), network design rules (design principles, wall crossings), the pipes (direct expansion, water pipes), air networks (vibration transmission through ducts, noise transmission through ducts, radiation of noise through the walls of the duct, design principles), acoustic attenuation devices (absorbers on walls, sound barrier, enclosures) and maintenance. **Heat pumps - study of the risk of noise pollution in the vicinity** covers measurements of residual noise without heat pumps, acoustic emergence, manufacturer documentation,	

conversion of acoustic power / pressure, place of installation (location, reflection of emitted noise), location of measurement and the measurement of acoustic emergence (absorbent on wall, sound barrier, enclosure).

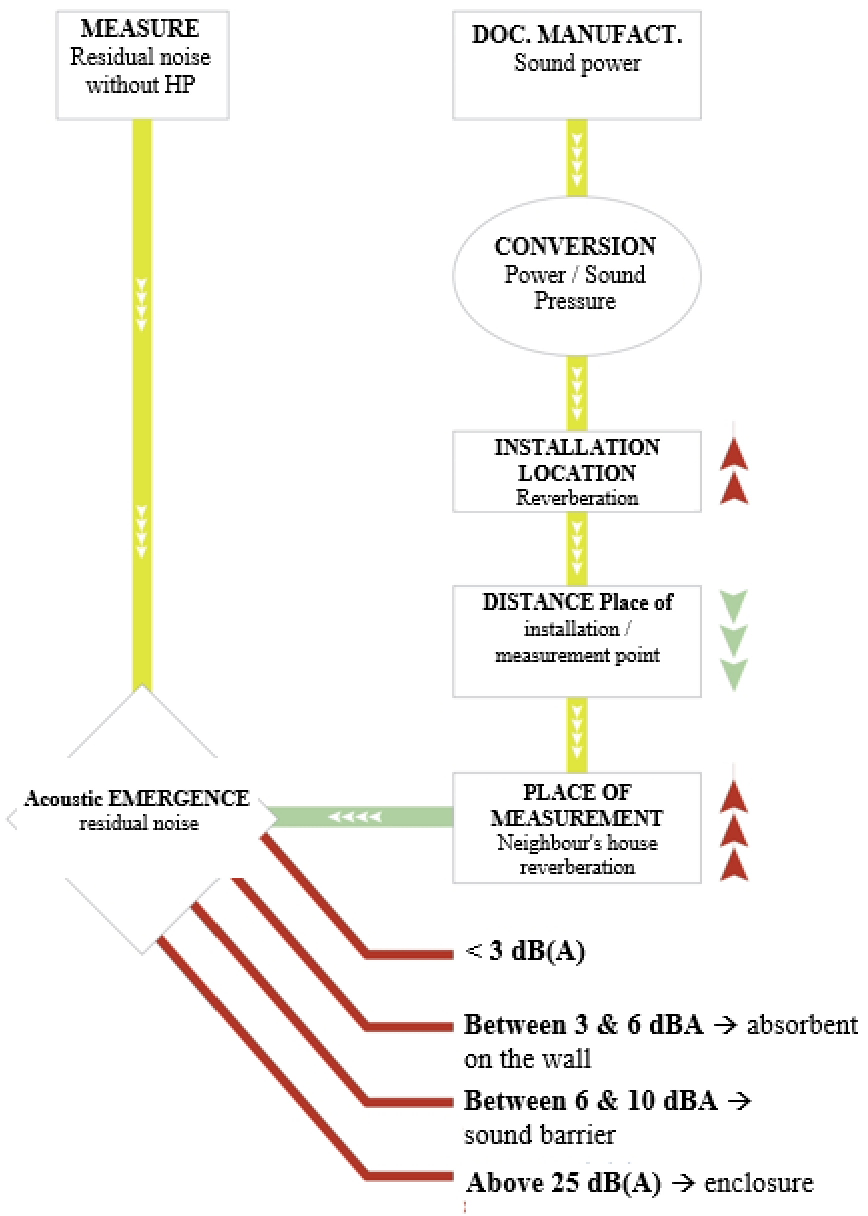


Figure 7-1: *Study of the risk of noise pollution in the vicinity [Source: . www.afpac.org]*

Deliverable 7.2 – **Workshop material and conference contributions** – **IEA HPT Annex 51 D7.2**	*7.2*
The 7.2 deliverable document, “7.2 Workshop material and conference contributions” lists all workshop presentations, the various conference presentations, contains the links to the webinar video (see first part of this document) and concludes with a list of publications which have been prepared by the Annex 51 partners throughout the Annex 51 duration:	

- E. Wasinger, *Sound field simulations of air-water heat pumps in a terraced housing estate*, Bachelor Thesis, Austria 2017, translated to English
- Ch. Reichl, J. Emhofer, M. Popovac, G. Drexler-Schmid, P. Wimberger, F. Linhardt, K. Alten, T. Fleckl, *International Research: Acoustic Signatures of Heat Pumps*, 11de Warmtepomp Synposium, Communicatiehuis, Gent, Belgium, October 10th, 2018
- Ch. Reichl, J. Emhofer, M. Popovac, G. Drexler-Schmid, P. Wimberger, F. Linhardt, K. Alten, T. Fleckl, *Akustische Emissionen von Wärmepumpen*, Chillventa Congress 2018, 5. Innovationstag Kältetechnik, Messe Nürnberg, October 14th, 2018
- P. Wimberger, J. Emhofer, C. Reichl, *MicLocator - Determine multiple microphones´ positions using sound wave delayand trilateration*, 68th Annual Meeting of the Austrian Physical Society, TU Graz; September 11th-13th, 2018
- S. Hinterseer, T. Bednar, *Determining the Influence of the Operating Point on Noise Emissions of Air Source Heat Pumps*, 68th Annual Meeting of the Austrian Physical Society, TU Graz; September 11th-13th, 2018
- Christoph Reichl, Johann Emhofer, *SilentAirHP - Advanced methods for evaluating and developing noise reduction measures for air heat pumps*, final report of Austrian research project, 21.08.2019
- Ch. Reichl, *Presentation on the Annex 51 and Experiences*, EHPA Sound Workshop, Vienna, 10.10.2019
- Thomas Fleckl, Christoph Reichl, *Annex 51 "Acoustic Signatures of Heat Pumps" in the framework of the International Energy Agency Technology Collaboration Programme on Heat Pumping Technologies (IEA HPT)*, Acoustics of Heat Pumps, Workshop at ICR2019, Montreal, Canada
- Johann Emhofer, Christoph Reichl, *1D modelling of heat pumps including acoustics*, Acoustics of Heat Pumps, Workshop at ICR2019, Montreal, Canada
- Christian Vering, Jonas Klingebiel, Markus Nürenberg, Dirk Müller, *Simultaneous energy efficiency and acoustic evaluation of heat pump systems using dynamic simulation models*, Acoustics of Heat Pumps, Workshop at ICR2019, Montreal, Canada
- Christoph Reichl, Peter Wimberger, Felix Linhardt, Johann Emhofer, *Acoustic Emissions and Noise Abatement of Air to Water Heat Pumps*, Acoustics of Heat Pumps, Workshop at ICR2019, Montreal, Canada
- Karlheinz Bay, Simon Braungardt, Thomas Gindre, Thore Oltersdorf, Jens Rohlfing, Lena Schnabel, Agostino Troll, *Testing campaign on the energetical and acoustical behaviour of a heat pump*, Acoustics of Heat Pumps, Workshop at ICR2019, Montreal, Canada
- Ola Gustafsson, Henrik Hellgren, Caroline Haglund Stignor, *Heat pump noise – operation dependence and seasonal averagin*g, Acoustics of Heat Pumps, Workshop at ICR2019, Montreal, Canada
- Troll, T. Gindre, *Charakterisierung der Geräuschentwicklung einer Wärmepumpe*, DAGA 2019 - 45. Jahrestagung für Akustik, Rostock, March 18th-21st 2019
- C.H. Kasess, C. Reichl, H. Waubke, P. Majdak, *Perception Rating of the Acoustic Emissions of Heat Pumps*, e Forum Acusticum, Lyon, France, December 7-11, 2020
- Christian H. Kasess, Christoph Reichl, Holger Waubke, Piotr Majdak, *Beurteilung derWahrnehmung der Schallemission von Wärmepumpen*, submitted to DAGA 2020, 46. Jahrestagung für Akustik, online 2020, Hannover, Deutschland

- Christoph Reichl, Johann Emhofer, Peter Wimberger, Felix Linhardt, Norbert Schmidbauer, Gerwin H.S. Drexler-Schmid, Brigitte Blank-Landeshammer, Andreas Sporr, Christian Köfinger, Thomas Fleckl, *Akustische Optimierung von Wärmepumpen (IEA HPT Annex 51)*, 26. Tagung des BFE-Forschungsprogramms «Wärmepumpen und Kälte», online BFH Burgdorf, 24.06.2020

- Christoph Reichl, Brigitte Blank-Landeshammer, Andreas Sporr, Gerwin Drexler-Schmid, Johann Emhofer, Mirza Popovac, Peter Wimberger, Camilla Sandström, Christian Köfinger, Andreas Zottl, Thomas Fleckl, *Acoustics of heat pumps with special focus on icing, defrosting and placement*, Chillventa eSpecial Congress, online, 13.11.2020
- Christoph Reichl, Johann Emhofer, G. Drexler-Schmid, Peter Wimberger, Felix Linhardt, Brigitte Blank-Landeshammer, Andreas Sporr, Thomas Fleckl, *Acoustic behaviour and placement of heat pumps*, The perception of sound and heat pumps" in The Essence of Heat Pumps Series, EHPA Webinar, 02.09.2020
- Blank-Landeshammer Brigitte, Sporr Andreas, Drexler-Schmid Gerwin, Kasess Christian, Köfinger Christian, Emhofer Johann, Waubke Holger, Reichl Christoph, *Noise Propagation Modelling and Mapping using Augmented Reality for HVAC Sound Sources*, submitted to ICSV27, 27th International Congress on Sound and Vibration, Prague, July 12th-16th, 2020, accepted, online 2021
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- Christian Vering, Jonas Klingebiel, Christoph Reichl, Johann Emhofer, Markus Nürenberg, Dirk Müller, *Simultaneous energy efficiency and acoustic evaluation of heat pump systems using dynamic simulation models*, submitted to the 13th IEA HPC, Jeju Island, South Korea, April 26-29, 2021

Note: Whereas, the IEA HPT Annex 51 documentation is in English, the documents of the Austrian national supporting project are in German and also available on the IEA HPT Annex 51 website.

8. Conclusions

The regulations examined are very opaque. It also seems to be very difficult for manufacturers and planners to determine which regulations apply where. Simplification and harmonization at both national and international level are urgently needed. Problems with acoustic noise emission only occur during operation or after neighbors have complained, e.g. when further heat pumps are installed - psychoacoustic effects also play a role: Anticipatory noise protection is of particular importance, since already sensitized persons may not or only partially perceive the improvement of the situation when noise protection is subsequently improved. In this sense, the design and placement of the heat pumps also play an important role.

In addition to frequency content, directionality is also extremely relevant to noise control measures. Their effect can vary depending on the direction of radiation and influence perception. In any case, limiting the information for the user to a single sound power level is too serious, because it also does not take into account the change in acoustic emissions due to transient processes. In this sense, a more comprehensive acoustic measurement within the certification measurements of heat pumps, which includes frequency content, directivity and transient effects, is highly recommended.

The investigations carried out in the IEA HPT Annex 51 collaboration show that the averaging of the temperature-dependent acoustic emissions can – to some extent - be represented by the appropriate choice of the measurement point. Thus, an acoustic "aSCOP" (Acoustic Seasonal Coefficient of Performance) is of great importance. The definition of a seasonal sound power level is an important means to represent the acoustic properties of heat pumps more realistically and to obtain a value representative for an estimation of the impact of the heat pump on the environment. However, in order to make reliable predictions, knowledge of the directionality and frequency content is crucial.

EN 12102 requires that the sound power of a heat pump may only be measured after a steady-state condition has been established for a prolongued period of time (30 minutes or 10 minutes after a de-icing operation). During this period, the operating conditions may change only slightly. However, in the course of icing, the flow and return temperatures change. Therefore, no steady-state condition is established during icing. At the same time, there can already occur an increase in sound power in the course of icing. It is therefore not always ensured, whether a measurement according to EN 12102 captures the maximum sound power of a heat pump.

The results from earlier studies but also from the current study show that, in addition to the A-weighted level, other acoustic, or psychoacoustic parameters such as loudness, roughness and sharpness influence the perception of annoyance. However, there is not a single parameter that can explain the perception, but it is shown that the combination of several parameters, first and foremost loudness, roughness and sharpness, can bring decisive improvements in the description of annoyance. Furthermore, it is shown that directionality has a decisive influence on annoyance judgments. It follows that the placement of a heat pump is an important issue and has an influence on the perception of annoyance.

9. Further Studies

In the course of the work, several research directions have emerged. In particular, the placement of heat pumps plays a very important role. This includes both the training of the respective installers and the provision of innovative tools to support the implementation decision in individual cases. Furthermore, it became apparent that direction- and frequency-dependent information on the sound radiation of heat pumps is an essential prerequisite for the establishment of innovative calculation methods - it therefore appears beneficial to include these quantities in some way in the usual measurements for obtaining certifications.

In the course of the activities in the national and international IEA HPT Annex 51, as well as inquiries from the industry, several topical fields have opened up, which could be considered in a follow-up collaboration. These are in particular:

- Field 1: Acoustics of heat pump arrays - optimal installation taking into account the formation of cold lakes depending on climatic conditions (temperature, humidity, wind direction and speed).

- Field 2: Acoustics of large heat pumps in industrial context

- Field 3: Indoor propagation of airborne and structure-borne sound from heat pumps installed indoors

- Field 4: Acoustic emission of outdoor heat pump units installed on the roof and influence on the environment considering psychoacoustic effects

- Field 5: Deeper investigation of the tonality of the units, as certain frequency bands are not evaluated - so different results can be obtained for the same units in different laboratories, causing confusion: although selected units are quieter from the measurement point of view, they are perceived louder.

- Field 6: Further investigation of directionality and establishment of an acoustic SCOP (aSCOP).

- Field 7: Refinement of measurement techniques by correlating simultaneously measured flow velocity, acoustics, and vibration signals.

- Field 8: Digitally assisted placement of heat pumps

These and more topics could be even the source of a follow-up Annex, which is to investigate special acoustic issues in specific use cases.

10. Recommendations

Heat pumps are an essential element for a more ecological heat supply in the future, both for hot water and for heating. In order to promote their further use, heat pumps should also be optimized with regard to acoustic parameters. Society should also be made more aware of noise emissions so that neighbors do not see every installation of a heat pump as an undesirable and disturbing source of noise from the outset. For the further spread of heat pumps, investment subsidies and signals that make the use of fossil fuels (oil, gas, etc.) less attractive are necessary.

In particular, the planning level and thus the placement of heat pumps is of great importance. This includes the optimization of heat pump arrays and positioning of large heat pumps as well as the digitally supported visualization of sound emissions, which is used to find an optimal position. With the replacement of conventional heating systems such as gas boilers in renovation projects by heat pumps, an intensive examination of sound and vibration propagation in building interiors also becomes necessary. The psychoacoustic treatment of these emissions has an important role to play, which must include tonality, directivity, frequency dependence and the treatment of transient effects. For the evaluation and thus a serious comparison of systems, a further analysis of an acoustic SCOP seems essential. In this sense, the required measurement technique for heat pump measurements in the laboratories has to be adapted in order to collect the relevant data.

11. The IEA HPT Annex 51 Team

A plethora full of highly skilled people contributed to the IEA HPT Annex 51. They are listed in the deliverable documents on the main pages. For each country one representative was selected given below:

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This umbrella report would not be complete without the group fotos generated during the visits at the contributing laboratories, only Italy missing due to the travel restrictions in 2020.

Figure 8-1: *Meeting fotos taken at AIT (Austria, 2017), CETIAT (France, 2018), RI.SE (Sweden, 2018), DTI (Denmark, 2019) and ISE (Germany, 2019) [Source: AIT, CETIAT, RI.SE, DTI and ISE]*

12. Administrative Topics

- Project duration: April 2017 – December 2020
- Operating Agent: Christoph Reichl, AIT Austrian Institute of Technology, christoph.reichl@ait.ac.at
- Participating countries: France, Sweden, Austria, Italy, Germany and Denmark

- Further information: http://heatpumpingtechnologies.org/annex51/ and Research Gate https://www.researchgate.net/project/IEA-HPT-Annex-51-Acoustic-Signatures-of-Heat-Pumps

13. Acknowledgements

This summary should not end without huge acknowledgments to all contributors within IEA HPT Annex 51. This has to be especially emphasized, as the last part of the Annex has been transformed to an online adventure due to the COVID-19 crisis, which also forced us to change the initially planned workshop at the Mostra Convegno Conference to a webinar. Acoustics of Heat Pumps will surely remain a topic of wild discussion and we are sure, that we can continue our way together to **increase the acceptance of heat pumps** by continuously removing the barriers one after the other. Enjoy the 500+ pages of documentations, the presentations, papers and last but not least the webinar.

All the best,

your IEA HPT Annex 51 Team.

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