Heating Ventilating and Air-Conditioning (HVAC) equipment taxonomy

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Abstract

Past efforts to reduce carbon emissions from the non-domestic building sector have had limited success in the UK. One of the reasons for this is a general absence of data addressing the non-domestic building sector, leading further to a lack of transparent and validated methods for energy use benchmarks and both statistical and predictive energy use modelling. This paper addresses this issue by proposing a Heating Ventilating and Air-Conditioning (HVAC) equipment taxonomy that will allow compatibility across building sector energy modelling, benchmarking and surveying.

The paper presents a comprehensive, yet easily expandable, friendly to use HVAC equipment taxonomy. The main aim of the HVAC equipment taxonomy is to assist both predictive and statistical building energy end use modelling, surveying fieldwork and analysis of all building types and the allocation of energy to end uses.

The HVAC equipment taxonomy developed also includes information about equipment energy efficiency in terms of efficiency coefficients or auxiliary energy consumption for both design and part load. This is supported by a review of what are sometimes contradicting and ill-defined energy efficiency indices, especially with regard to part-load operation.

Introduction

Promoting energy efficiency in buildings in the European Union has gained prominence with the adoption of the Directive on Energy Performance of Buildings (EPBD) in 2002. The EPBD requires several different measures to achieve prudent and rational use of energy resources and to reduce the environmental impact of energy use in buildings. The three main components for implementation of the Directive are: calculation methodology, energy certificate and inspections of boilers and air-conditioning. The principal categories for the energy certificate scheme are Asset Rating, based on calculated energy use and Operational Rating, based on metered energy. The imminent, April 2008, implementation of the energy certificate scheme in the UK has revealed that existing sets of benchmarks were limited and that design data is unlikely to be available in existing building stock.

More recently, under the EU Energy Efficiency Action Plan, the UK has committed to an indicative target of 9% energy saving by the end of 2010 and the next Action Plan in 2011 must report on progress against this. Although the targets are indicative and thus not mandatory, Member States have a clear legal obligation to adopt and aim to achieve the target, using appropriate cost-effective energy services and other energy efficiency improvement measures, with the building sector already identified as one having the largest cost-effective saving potential.

The successful implementation of any energy efficiency measure in the building sector and especially the evaluation of its extent are virtually impossible without detailed knowledge of the current energy profile of the UK building stock. While there is, to some extent, already existing information on domestic stock there is much less information available on the non-domestic sector. The steady increase in air-conditioning and appliances such as computers, telephony and various amenities use in non-domestic building sector has been observed and identified as a potential area for decreasing the overall building energy consumption (Careiro 2006, Brow 2007, Marjanovic-Halburd 2008). At the same time there is little or no information on the air-conditioning systems presence in existing buildings, let alone their type distribution. The lack of statistics on UK non-domestic building stock makes that sector a priority. Its diversity in both activity and built forms renders it much more complex than domestic sector.

Energy end-use in non-domestic buildings is usually grouped in following categories:

- Energy used for building heating, ventilating and air-conditioning which is consumed by building HVAC equipment,
- Energy used for domestic hot water provided either by building heating source or by dedicated domestic hot water heaters,

- Energy used for lighting consumed by lights and
- Energy used by different appliances that can be anything from desk top computers over vending machines to hand dryers in toilets.

Often, the energy used by fans, pumps and controls, which are strictly speaking part of the HVAC equipment, are accounted as a separate category generally referred to as 'auxiliary' and associated with electrical energy.

In order to understand non-domestic building energy consumption contributing to energy end use categories and their subsequent carbon emissions, it is necessary to have information about the HVAC equipment and appliances used in buildings, together with the way they are used, as well as the building characteristics. The HVAC taxonomy presented in this paper is part of a wider research programme addressing this issue by developing a data system which will include different taxonomies (appliances, HVAC systems, building types, etc…) and surveying protocols, thus enabling both statistical and predictive modelling of the energy end-uses in non-domestic buildings.

HVAC Taxonomy

The central aim of the research described in this paper is to provide a general purpose HVAC equipment classification to assist both statistical and predictive energy end-use modelling and surveying field work for both the domestic and non-domestic buildings. Surveying can be at different levels of detail and the HVAC Taxonomy must therefore support different levels of surveying complexity through several tiers. Ideally the taxonomy would subdivide HVAC equipment into a number of clear and systematically grouped categories whilst being at the same time both comprehensive and complete, i.e. there is a place for everything, and only one place. This would avoid over-complication of the survey process whilst maintaining the desired level of accuracy. The more general tiers should be detailed enough to still allow reasonable accuracy when used for modelling purposes. The energy end-use modelling in this concept refers to a steady-state monthly or yearly prediction in which case the efficiencies and/or coefficients of performance (COPs) of the HVAC systems and its elements would be one of the most important modelling parameters. The developed taxonomy should facilitate the modelling process by providing default values of efficiency at different classification levels for both design, nominal, and part load efficiencies.

There are a large number of variations in HVAC equipment and the ways they can be used to control the environment. The usual approach in building services text books and design manuals in classifying air conditioning systems is to distinguish one type from another and to provide a background for selecting the optimum air conditioning system based on building requirements which usually results in the classification based on working fluids as all-air, all-water or air-water (ASHRAE Handbook 2000).

The existing approach typically used by HVAC equipment manufacturers is usually centred around the individual processes for which specific HVAC equipment is responsible for. A good example of the latter system of HVAC classification is given by OPUS (www.opus-bs.co.uk), Figure 1.

Air conditioning and refrigeration

- Air conditioning, air/water
  - Air conditioning/ventilation system maintenance (U33)
  - Fan coil air conditioning, fan coil units (U30)
  - Induction air conditioning, induction units (U29)
  - Terminal heat pump units, heat pump/cooling units (U32)
  - Terminal re-heat air conditioning, terminal box (U31)
  - Underfloor air conditioning systems (U41)
- Air conditioning, all air
  - Dual duct air conditioning, mixing/blending units (U28)
  - Variable air volume (VAV) equipment, pressure reducing dampers (U25)
  - Variable air volume (VAV) terminal units (U26)
  - Variable refrigerant flow (VRF) equipment (U27)
- Air conditioning, hybrid
  - Hybrid air conditioning (U34)
- Air curtain systems
  - Air curtains (U39)
- Central refrigeration/distribution
  - Adiabatic dry coolers (T65)
  - Compressors (T66)
  - Condensing units (T67)
  - Cooling towers (T68)
  - Glycol chillers (T69)
  - Heat pumps, commercial/industrial (T28)
  - Heat pumps, domestic (T29)
  - Hybrid dry coolers
  - Ice thermal storage units (T70)
  - Refrigerant plant, direct expansion (T72)
  - Refrigerant plant, water chillers (T73)
  - Refrigerants and lubricants (T71)
- Local cooling/refrigeration
  - Cold rooms and components (T77)
  - Cooling units, packaged (T74)
  - Ice pad components (T78)
  - Local cooling units (T75)
  - Water coolers (T76)
- Unitary air conditioning
  - Air conditioning units (U37)
  - Air conditioning units, gas fired (U35)
  - Air conditioning units, maintenance/cleaning (U38)
  - Air conditioning units, room packaged (U36)

Heating

- Boilers, parts and accessories
  - Airless drying (T34)
  - Boiler instrumentation (T01)
  - Boiler pressurisation (T02)
  - Boilers, domestic, coal fired, natural draught (T21)
  - Boilers, domestic, gas-fired (T03)
  - Boilers, domestic, oil-fired (T04)
  - Boilers, exhaust gas (T32)
  - Boilers, industrial/commercial, coal fired (T22)
  - Boilers, industrial/commercial, hot water, dual gas/oil-fired (T05)
  - Boilers, industrial/commercial, hot water, gas fired (T06)
  - Boilers, industrial/commercial, hot water, oil fired (T07)
  - Boilers, industrial/commercial, steam, gas/oil fired (T08)
  - Boilers, multi-fuel (T33)
  - Burners (T09)
  - Burners, accessories (T10)
  - Burners, solid fuel (T23)
  - Chimneys, flues and accessories (T14)
  - Chimneys, flues and accessories, anti down-draught terminals (T11)
  - Chimneys, flues and accessories, balanced flue chimney systems (T12)
  - Chimneys, flues and accessories, chimney and flue systems (T13)
  - De-aerators, spray type (T15)
  - Economisers (T16)
  - Electric and electrode boilers (T26)
  - Handling systems, ash (T24)
  - Packaged steam generators (T27)
  - Steam boilers, blow-down accessories (T17)
  - Steam injection heaters (T18)
  - Steam vent silencers (T19)
  - Superheaters (T20)

- Heat distribution/utilisation, air
  - Combined warm-air/hot-water units (T49)
  - Convector heaters, gas fired (T59)
  - Other local heating units (T60)
  - Radiant heating systems, gas fired (T58)
  - Warm air heaters, ducted (T53)
  - Warm air heaters, gas fired (T54)
  - Warm air heaters, multiple fuel (T55)
  - Warm air heaters, oil fired (T56)
  - Warm air heaters, portable (T57)
  - Warm air heating systems, gas fired (T50)
  - Warm air heating systems, multiple fuel (T51)
  - Warm air heating systems, oil fired (T52)
- Heat distribution/utilisation, water
  - Ceiling systems, heating/cooling (T42)
  - Condensate pumping sets (T45)
  - Convector heaters, mthw/lthw (T35)
  - Convector heaters, steam (T46)
  - Cooling systems, underfloor/in-wall/ceiling (T44)
  - Heating/cooling systems, embedded panel (T43)
  - Radiant heaters, mthw/lthw (T36)
  - Radiant heaters, steam (T47)
  - Radiator accessories, reflecting panels (T37)
  - Radiators, aluminium (T38)
  - Radiators, cast iron (T39)
  - Radiators, plastic (T40)
  - Radiators, steel (T41)
  - Steam generators (T48)
- Heat recovery
  - Heat recovery equipment, air-to-air (T61)
  - Heat recovery equipment, general (T62)
  - Heat recovery equipment, refrigerant (T63)
  - Heat recovery equipment, steam condense (T64)

Figure 1: OPUS HVAC classification (www.opus-bs.co.uk)

As already mentioned the purpose of this research is to develop a HVAC taxonomy that would support both statistical presentation of different HVAC systems and/or equipment in non-domestic buildings and predictive modelling of the building HVAC energy end-use in this sector. The text book approach of having a few broad categories is too general and would allow neither sufficiently robust statistical HVAC modelling nor statistical analysis. On the other hand, the manufacturers' style of HVAC equipment classification is a practical, detailed list of the available products with far too many details to effectively support the surveying fieldwork or effective predictive energy-end use modelling at the building stock level.

The AuditAC project (AuditAC Training Package), concerned with air-conditioning systems mandatory analysis as part of the European EPBD implementation, has suggested the following classification, Figure 2.

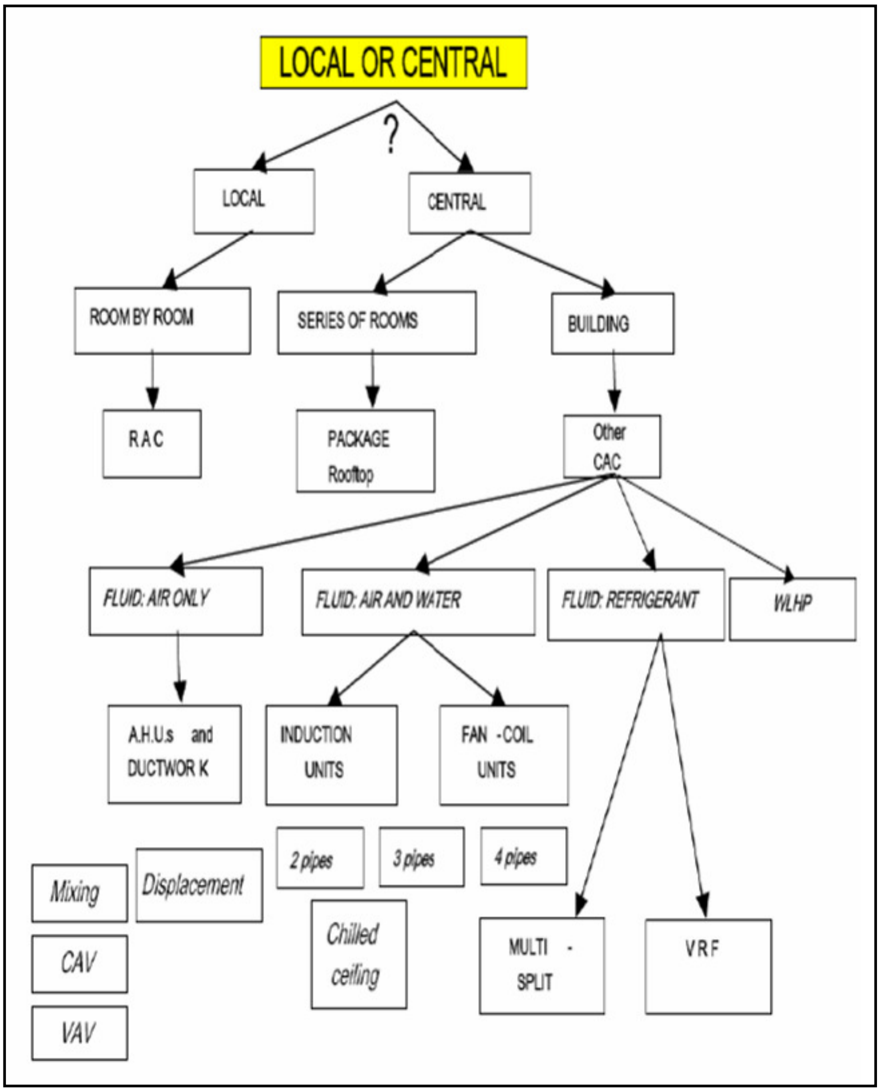

Figure 2: AuditAC HVAC system classification (AuditAC Training Package)

Although more suitable than other classification methods previously described, its primary classification at room and building level is not definitive, since one can have several different air conditioning systems in the same building, each of them serving one or several rooms.

The new classification is based on existing methods but is concerned with both surveying fieldwork and HVAC energy-end use modelling. It is summarised in Table 1.

Table 1: HVAC systems classification

HVAC Equipment					η / COP
Individual HVAC Units					
	Heating Only				
		Storage Heaters			1
			Old		
			New		
			Fan Assisted		
		Room Heaters			
			Electricity		1
			Gas		0.65
			Oil		
			Solid		
			Biomass		
		Open fire			
			Solid		
			Gas		
			Biomass		
		Stoves			
		Overhead Radiant Heaters			
			Unflued		0.7
			Flued		0.6
			Multi-burner		0.65
	Air Conditioning				
		Window AC Unit			
		Portable			
		DX (VRF)			
			Split System		
			Cassette		
Unitary Packaged Systems (VRF)					4.3
	Cassette				
	Ducted				
Primary Central Hydronic Systems					
	Boiler				
		Domestic			
			Electricity		
			Gas		
				Condensing	0.9
				Non-condensing	0.65
			Oil		
			Solid		0.5
		Medium			
			Gas		
				Condensing	
				Non-condensing	
			Oil		
			Solid		
		Large			
			Gas		
			Oil		
			Solid		
		Multi (n>=2)			
			Gas		
			Oil		
			Solid		

Table 1: HVAC systems classification (continue)

HVAC Equipment					η / COP
Primary Central Hydronic Systems					
	District				1
		Heating			
		Cooling			
	CHP				
	Chiller				2.5
		Air Cooled Condenser			
		Water Cooled Condenser			
		Cooling Tower			
	Thermodynamic cycle (Thermal Engine)				0.9
		Vapor Compression			
		Absorption Systems			
		Desiccant Systems			
Secondary Central Hydronic System					
	Heating Only				
		Radiators			
		Convectors			
		Radiant Panels			
	Air Conditioning				
		All air			
			Single zone CAV (Constant Air Volume)		
			Multi zone CAV		
			VAV (Variable Air Volume)		
				Single Duct	
				Dual Duct	
			Thermoduct systems		
		Air-Water			
			Radiators		
			Convectors		
			Chilled Ceiling		
			Unite Heaters		
			Fin-Tube		
			Base-Board		
			Radiant Panels		
			Fan-Coil Units		
			Induction Units		
		All Water			
			Radiant Panels		
			Fan-Coil Unit		
			Induction Unit		

HVAC equipment efficiency

Boiler efficiency

ASHRAE gives the definition of the boiler efficiency as the ratio of energy delivered by the water as it leaves the boiler and the energy in the fuel delivered to the boiler, whilst the seasonal efficiency is “Actual operating efficiency that the boiler will achieve during the heating season at various loads…”, (ASHRAE, 2004). It should be noted that there are two efficiency figures, depending on whether the gross or net calorific value of the fuel is used.

UK Building regulation defines the seasonal efficiency based on the boiler efficiencies, measured at 100% load ($\eta_{100\%}$) and at 30% load ($\eta_{30\%}$) which are usually quoted by the boiler manufacturers, (DCLG, 2006). For single boiler systems where the boiler output is ≤ 400kW and the boiler will operate on a low temperature system, and for multiple-boiler systems where all individual boilers have identical efficiencies and where the output of each boiler is ≤ 400kW operating on a low temperature systems the following equation applies:

Seasonal Boiler Efficiency = 0.81 $\eta_{30\%}$ + 0.19 $\eta_{100\%}$ equation (1)

If we make an analogy with the part load efficiency of chillers according to the ARI standard, this would imply an underlying assumption that boilers operate 81% of their working time at 30% load and 19% at full load. There are no relations in this equation to any of building load parameters, such as water mass flow rate, flow or return temperature. By its definition, the seasonal efficiency should be used to predict the annual fuel consumption: however, the seasonal efficiency is often used in simulations, multiplying the global efficiency figure directly by building load to produce a monthly or even daily energy consumption profile.

From 1st of January 1994 all new hot water boilers in the UK must operate at minimum levels of efficiency whilst running at full-load or part-load conditions, (DTI, 1995). All boilers must comply with the following efficiency requirements at full load and at 30% part load (Table 2). The efficiencies are classified into three categories depending on the average boiler water temperature at part load. The average boiler water temperature is the average of entering and leaving boiler water temperature which indirectly connects to building loads. Efficiencies are calculated using the boiler rated power output Pn.

Table 2: Boilers useful net efficiency requirements

Type of boiler	**Range of output power**	**Efficiency at rated output**		**Efficiency at part load**	
	kW	**Average boiler water temperature [°C]**	**Efficiency requirement [%]**	**Average boiler water temperature [°C]**	**Efficiency requirement express in %**
Standard	4 to 400	70	≥84+2LogPn	≥50	≥80+3LogPn
Low temperature (*)	4 to 400	70	≥87.5+1.5LogPn	40	≥87.5+1.5LogPn
Gas condensing	4 to 400	70	≥91+LogPn	30 (**)	≥97+LogPn

(*) including condensing boilers using liquid fuel
(**) temperature of boiler water supply

If we combine the equation (1) and the requirements from the Table 2 we obtain the following equation for standard boilers:

SBE_{min}=80.76 + 2.81logPn equation (2)

Equation (2) suggests that the minimal seasonal efficiency is 82.45% for small boilers (4 kW) and goes up to 88% for 400kW boilers. At the same time CIBSE in (CIBSE, 2005) is suggesting typical seasonal efficiencies for non condensing boilers in the range of 45%-82%, Figure 3.

Table 4.2 Typical seasonal efficiencies for various boiler types(3)

Boiler/system	Seasonal efficiency(%)
Condensing boilers:	
- under-floor or warm water system	90
- standard size radiators, variable temperature circuit (weather compensation)	87
- standard fixed temperature emitters (83/72 °C flow/return)*	85
Non-condensing boilers:	
- modern high-efficiency non-condensing boilers	80-82
- good modern boiler design closely matched to demand	75
- typical good existing boiler	70
- typical existing oversized boiler (atmospheric, cast-iron sectional)	45-65

* Not permitted by current Building Regulations

Figure 3: Boiler efficiencies, (CIBSE, 2005)

As already mentioned, often the boiler seasonal efficiency is used for short-term HVAC energy end-use modeling. However the accuracy of the modelling prediction would increase if the boiler efficiencies are given as a function of the part load conditions, thus relating more closely to the actual operating efficiencies which depend on the operating conditions.

CIBSE Guide B shows the boiler efficiency changes with variations in boiler load as in Figure 4. However it is rather difficult to relate "boiler load" with variables associated with the building load such as water temperatures or flow rates. ASHRAE, on the other hand, at least for condensing boilers, suggests the use of a relationship between the boiler efficiency and return water temperatures, see Figure 5, which can be related to the system operating conditions. However, this approach does not account for variation in water flow rates or air-fuel ratio in operation.

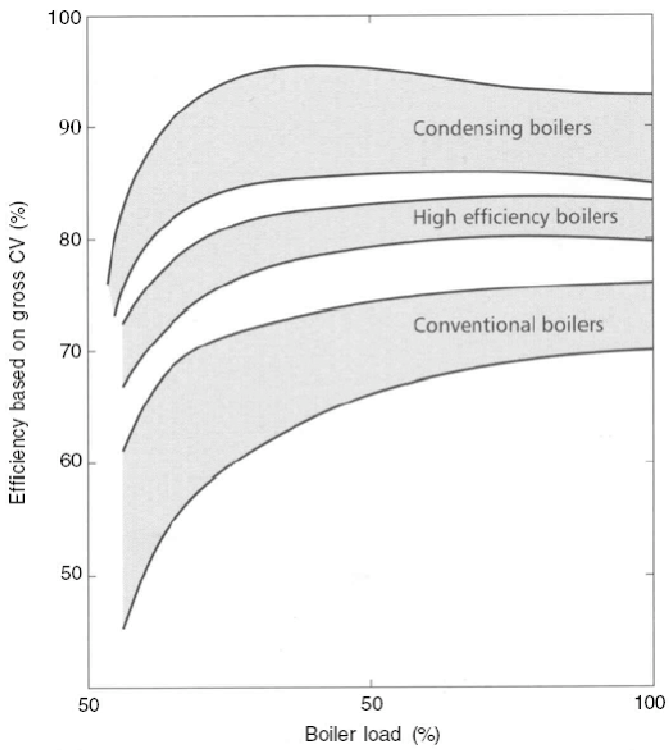

Figure 4: Typical seasonal LTHW boiler efficiencies at part load, (CIBSE, 2005)

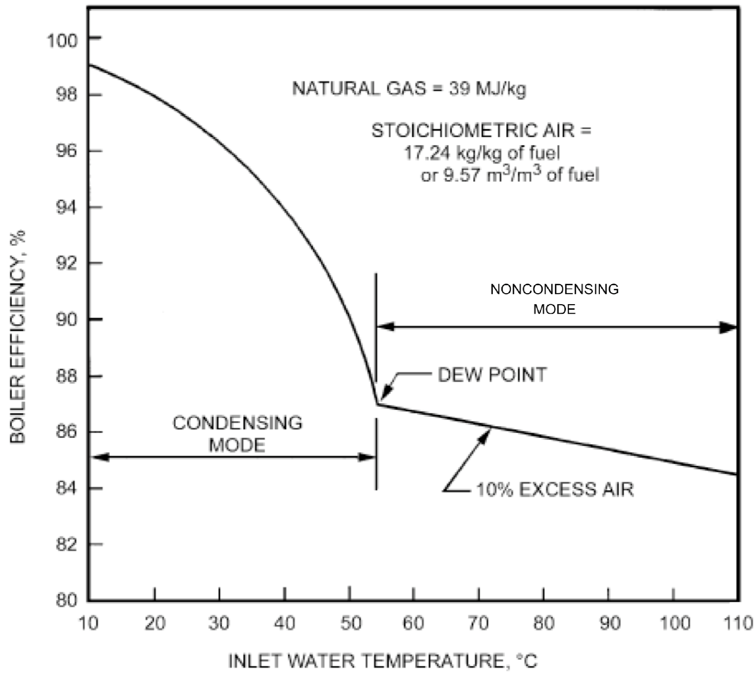

Figure 5: Boiler efficiency – effect of inlet water temperature, (ASHRAE, 2004)

Recent research (Hanby, 2007, Andre 2008) on boiler efficiency based on physical modelling of the boiler components has shown how all the operating characteristics can be taken into account. The example summary graph presented in Figure 6 includes both the boiler's flow and return water temperatures.

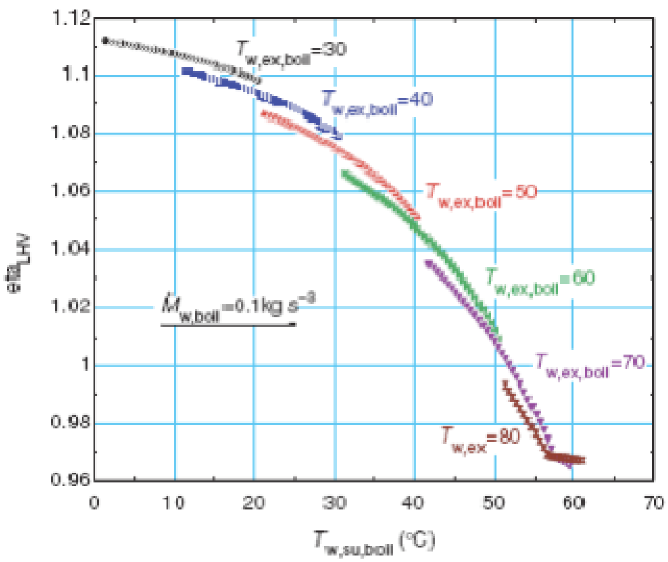

Figure 6: Evolution of the boiler net efficiency with the boiler water inlet (return) temperature for different values of the outlet water (flow) temperature, (Andre, 2008)

The results presented in Figure 6 show the significance of the water return temperature, particularly in the region where flue gas condensation begins (around 55C).

Chiller efficiency

The other HVAC component crucially influencing HVAC energy end-use is the chiller when the building is air-conditioned. The usual way of presenting the energy efficiency of chillers is by the coefficient of performance (COP) and integrated part load value (IPLV). For example, according to Canada's Energy Efficiency Regulations, water chillers must meet the minimum COP and IPLV presented in Table 3.

Table 3: Minimum COP and IPLV of Packaged Water Chilling Packages (CSA C743-02 Performance Standard for Rating Packaged Water Chillers / Canadian Standards Association)

Type	**Capacity range [kW]**	**COP**	**IPLV**
Air-Cooled with Condenser	<528	2.8	3.05
	≥528	2.8	3.05
Air-Cooled without Condenser	all	3.10	3.45
Water-Cooled, Reciprocating	all	4.20	5.05
Water-Cooled, Rotary Screw, Scroll	<528	4.45	5.20
	≥528 and ≤1055	4.90	5.60
	>1055	5.50	6.15
Water-Cooled, Centrifugal	<528	5.00	5.25
	≥528 and ≤1055	5.55	5.90
	>1055	6.10	6.40

As the most common COP values for water and air cooled chillers of 4.2 to 5.4 and 2.7 to 3.2 respectively are suggested in (Yu, 2006).

According to ARI Standard 550/590, the IPLV should be determined using the part-load energy efficiency at 100%, 75%, 50%, and 25% load points at the specified conditions, equation (3).

$$\mathrm{IPLV} = 0.01{*}\mathrm{COP}_{25\%} + 0.42{*}\mathrm{COP}_{50\%} + 0.45{*}\mathrm{COP}_{75\%} + 0.12{*}\mathrm{COP}_{100\%}$$ equation (3)

The ARI standard has been challenged by work presented by Yu in (Yu 2000), where it has been demonstrated that when variable condensing temperature control was present, the ARI performance curves could give inaccurate information about the maximum COP at part loads.

The importance of chiller part load efficiency on HVAC end energy use is well captured in EnergyPlus simulation software where performance curves for more than 160 chillers are provided. EnergyPlus, in its chiller model, uses performance curves based on leaving chilled water temperature and entering condenser water temperature. The influence of the building cooling to the chiller efficiency is introduced indirectly through the part load factor which is based on the real building cooling load.

Conclusions

This paper presents a comprehensive, yet easily expandable and easy to use general purpose HVAC equipment classification that covers both the domestic and non-domestic building sectors. The purpose of developing the taxonomy is to facilitate both predictive and statistical building energy end use modelling, surveying fieldwork and analysis of all building types and the allocation of energy to end uses.

In tandem, the taxonomy needs to be aligned to values and procedures for calculating energy conversion factors for the class members. A brief review covering boiler and chiller full-load and part-load efficiencies has been presented, to illustrate how these two aspects can be combined.

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