EUDP 11-I, J. no. 64011-0076

Heat Pumps for Domestic Hot Water Preparation in Connection with Low Temperature District Heating

Appendix 1: Heat Demand Analysis

Note on energy demand and peak power for space heating and DHW for houses build in accordance with BR15

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Work Package 02

List of abbreviations				
AHU	Air handling unit		HREC	Heat recovery
DH	District heating		PI-reg	PI regulator
DHN	District heating network		SH	Space heating
DHW	Domestic hot water		TH	Thermostat
FH	Floor heating		EKV	Equitherm - weather compensated control
HG	Internal heat gains			
HP	Heat pump			

Note on energy demand and peak power for space heating and DHW for houses build in accordance with 2015

This note reports on energy demand (heat load curves) and peak power demand for Space Heating (SH) and Domestic Hot Water (DHW) based on dynamic numerical simulation in IDA-ICE software (1).

The energy demand is calculated/simulated for two types of single-family houses build in accordance with class 2015 (2). The first house is semi-detached house with gross area 95 m^2, the second house is stand-alone single family house with gross area 159m^2. Both houses are aimed to be supplied by district heating (DH) system.

The energy demand for the newly build building should fulfil requirements defined by Building Regulations (BR), recently BR10 (2). BR10 specifies three different classes for energy demand. The reference level is class BR10 and the energy demand is reduced for buildings in class 2015 and even more for class 2020. The energy demand for residential buildings accounts an energy for space heating and DHW heating and energy needed for operation of ventilation system and pumps for building services. The energy frame for residential building in accordance 2015 is defined by equation

$$30 + 1000 / \text{heated area (gross)}$$

The left column of Table 1 shows overview of input parameters used for calculation of energy demand in accordance with BR10.

Table 1 – comparison of input values required by BR10 and expected real values

	values in accordance with BR10 & Anv213	expected real values
DHW demand	250L/(m2.a) of 55°C warm DHW (2) (3)	800kWh of DHW (45-10) per person (4)
Internal heat gains	5W/m2 (heat gains on inner area)	5W/m2 or 3W/m2
Set point temperature for space heating	t_{air}=20°C	$t_{operative}$=22°C (24°C in bathroom)

Nevertheless the values required by the BR 10 energy frame calculation are different from the values measured during real use of the building. The difference between energy demand theoretically calculated and measured in reality is documented e.g. in (5) where preferred set-point temperature in single-family house is 22°C (24°C in bathroom) instead of 20°C suggested by BR10. The right part of the Table 1 shows values expected in for real use of building.

We performed simulations for required BR10 values as well for expected real values and thus we can see the expected difference.

1 Definition of simulated cases

1.1 General values

In order to cover different possible user behaviour, we defined three different cases (see Table 2).

Table 2 – definition of simulated cases

case	set-point temperature [°C]		heat gains [W/m2]	DHW
A	air temperature	20	5	250 of 55°C L/(m2.a)
B	operative temperature	22/24	5	800kWh/person.a
C	operative temperature	22/24	3	800kWh/person.a

- Case A – in accordance with BR10 and Anv213 requirements
- Case B – due to expected users behaviour (space heating set-point temperature 22°C (bathroom 24°C) and higher DHW demand)
- Case C – same as case B, but internal heat gains are reduced to from 5W/m2 to 3W/m^2

1.2 Infiltration

Infiltration has very big influence on energy demand of the new buildings with reduced heat demand. Table 3 gives overview of maximal infiltration rates for different BR10 classes.

- **Table 3 – Maximal allowed infiltration in the houses due to BR10 requirements**

	BR10	class 2015	class 2020
Maximal infiltration q50 for 50 Pa difference [L/m2.s]	1.5	1	0.5
Maximal infiltration for 0 Pa [L/m2.s] recalculated based on eq. 0.04 + 0.06*q50 [SBI Anv. 213]	0.13	0.1	0.07

The building is simulated in accordance with 2015 requirement with an infiltration 0.1L/m2.s for heated area, i.e. 159 and 95m^2.

1.3 HVAC Systems

1.3.1 Ventilation

Flow rates for ventilation system were designed in accordance with BR10 requirements (see Table 4) for exhaust from defined rooms. The supply flow rate was designed to make the ventilation balanced by supplying air to other rooms.

Table 4 – requirements for ventilation design

room	direction	flow [L/s]
kitchen	exhaust	**20**
technical room	exhaust	**10**
WC/bad	exhaust	**15**

Values specifying AHU are defined in Table 5.

Table 5 – AHU specification

AHU	
Heat recovery efficiency	85%*
Efficiency of heating coil for ventilation (supplied by DH)	100%
t_{supply} air	18°C, continuously (unit without cooling coil)

*value 85% is based by reduction of 10% from value of manufacturer in order to be on safe side

The air flow between individual rooms is allowed by gap between doors and floor. The gap area needed (i.e. height of door which should be cut) is calculated from continuity equation V_{dot}=A*w, where w=0.5m/s, chosen as a maximal value preventing problems with draft and noise.

1.3.2 Space heating

Space heating is provided by floor heating. The composition of the floor can be found in Appendix for individual cases. The spacing for individual pipes is 300mm and inner pipe diameter is 10 mm if is not stated different number. H value (EN15377-1) is expected to be 15W/m2.K, and centre of the pipes is situated 8 cm below the floor surface if not stated differently.

Each room has an individual loop with on/off electronic valve. The flow rate in the individual floor heating loops is constant. The electronic valve is controlled by temperature sensor (operative temperature) placed in individual rooms. Temperature of heating water supplied into FH system is controlled by weather compensated (sometimes called “equitherm”) curve. The curve is shown in Figure 1.

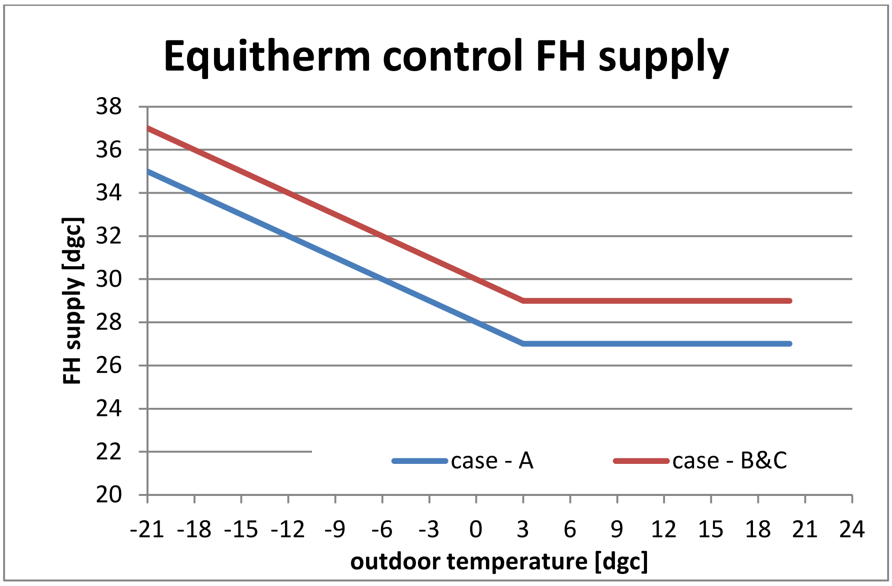


Figure 1 – Weather compensated control for FH

Supply water to FH is mixed in mixing loop from 40°C DH water and water returning from FH system.

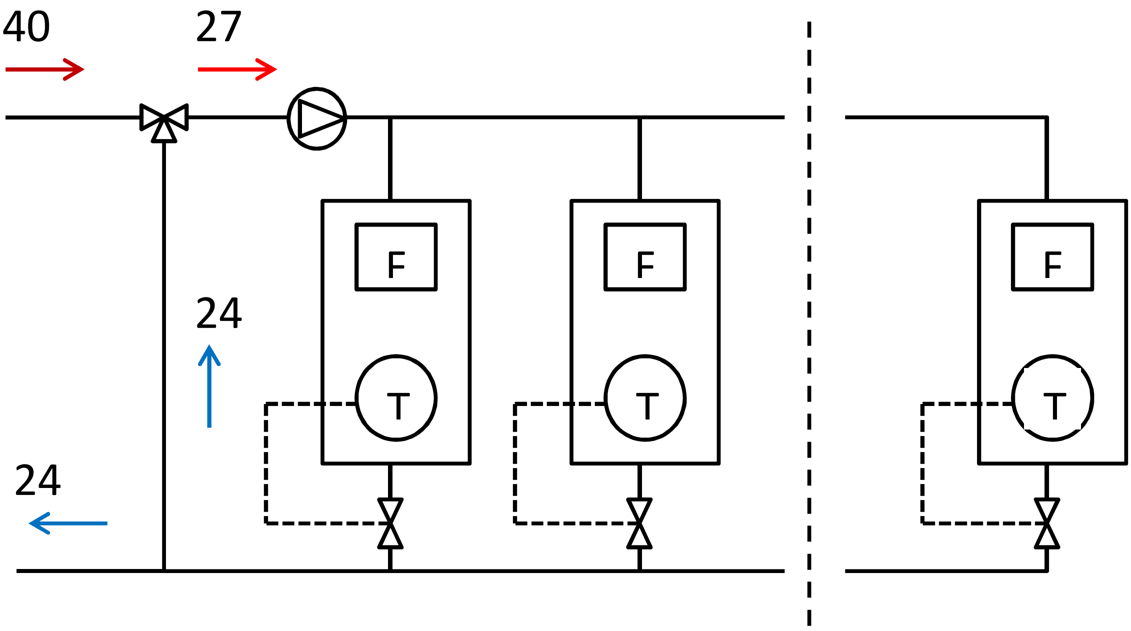


Figure 2 – scheme of FH system design

Low supply temperature is chosen by requirement to have return temperature as low as well as design temperature drop on the circuits 3K to assure uniform floor temperature and comfort for occupants.

1.3.3 DHW

Independently on number of people in the house or type of DHW heater, the heater should be able supply DHW with energy 32.3 kW for flow pattern defined in DS439 (6).

The DHW is heated in developed DH substation combined with HP. The heat loss from the developed substation is expected 96W and 90W for room air temperature 20°C and 22°C.

The values are based on calculation that average temperature of the unit is 52°C and heat loss coefficient UA = 3W/K (previously measured for similar unit, LGM120 substation in Lystrup (5)).

$$H_{loss}=(52-20)*3=96W$$

1.4 Weather & orientation

The simulations were performed with weather file DRY Danmark (design reference year for Denmark).

The orientation of the houses is by entrance to the south.

2 Methods

Both houses were modelled in IDA-ICE (1) software, version 4.2. For each house, we simulated 3 different cases of input parameters (see Table 2, above). The result of the simulations is a heat demand curve of the house and peak power for the space heating system including AHU heater.

Comparison of IDA model with Be10 calculation

To prove that both houses are designed in accordance with BR10 and fits required energy frame, the energy demand should be documented by calculation in BE10 software. Anyway for detailed simulation of heating peak demand other software, in our case IDA-ICE, should be used. To assure that the models of the houses in IDA-ICE correspond to the model made in Be10 we compared results from both software.

Peak heat demand reduction for floor heating

One of the required results is a peak power demand for SH system. A peak heat demand of FH is sometimes unnecessarily high and thus misleads to over dimension of heat sources and DHN which leads to higher heat losses.

Peak demand for FH can be to some extent limited without significant influence on thermal comfort in the rooms [(5)task 3 – flow limiter].

Figure 3 shows heating power needed for whole house 3B and operative temperature in room 12.8 for coldest day in DRY, i.e. 8th January. There are three cases. In first case, the power to SH system is not limited and for second and third case the maximal heating power is limited to 3 and 2 kW, respectively.

It can be seen that in case 2 with maximum heating power 3 kW, the operative temperature in room 12.8 drops maximally to 19.65°C, while in case 1 with unlimited power (maximal value is 6kW) the minimal temperature is 19.84°C. The difference in minimal operative temperature is only 0.2 K, which is considered as marginal in thermal comfort, but the design maximal heating power decreased from 6 kW to 3 kW which is very important.

Further reduction of maximal heating power to 2 kW (third case) will results in operative temperature reduced to 19.34°C. Based on the results we conclude that maximal power of 3 kW is the safe value for design heating power for space heating system in house 3B.

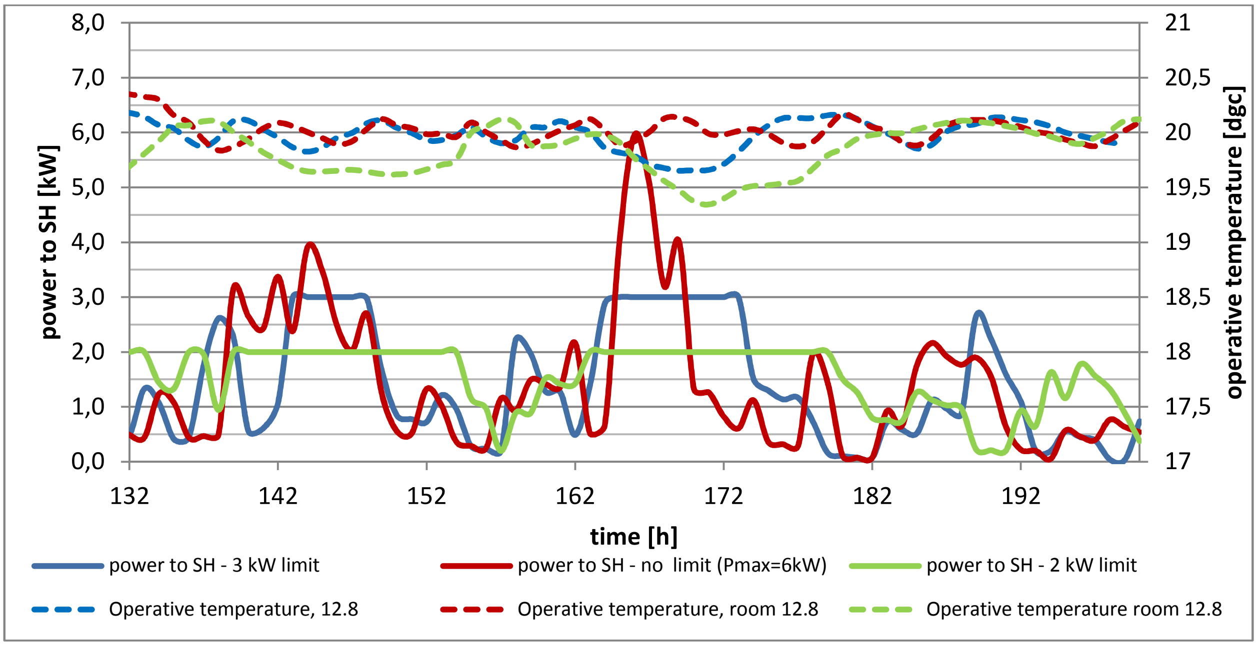


Figure 3 – averaging of peak power (will be improved by figure from IDA)

Heat loss from DHW storage tank

The heat loss from storage tank was modelled as constant continuous heat gain (96W and 90W for case A and B&C respectively, not considering changes of air temperature in the technical room, where the unit is placed.

3 Investigated houses

3.1 Description

Detailed description of individual systems and construction is listed in Appendix.

3.1.1 Type house DLV 159 from LIND&RISØR

The type house DLV159 with gross area of 159m^2 (7) is considered as a typical example of single-family house with one storey and pitched roof. The house was originally designed for energy frame 2010, but we modified the structures (increase thickness of insulation and use better windows) to fulfil requirement 2015. The optimization of the house for class 2015 was made in Be10 software (8).

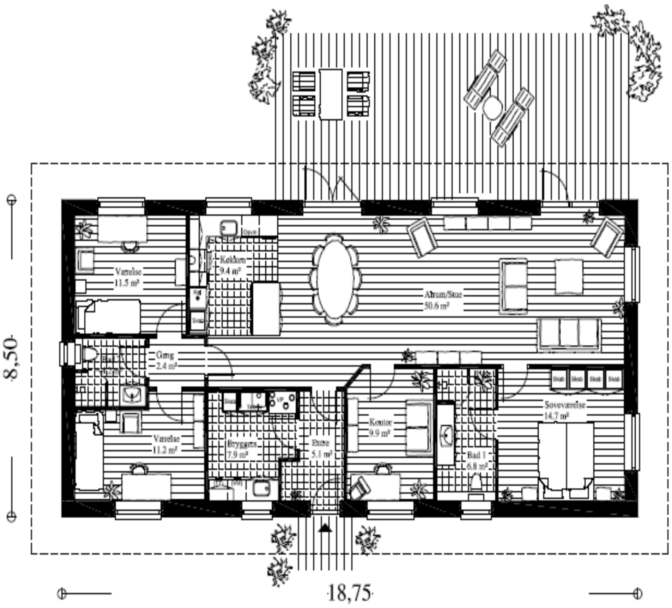
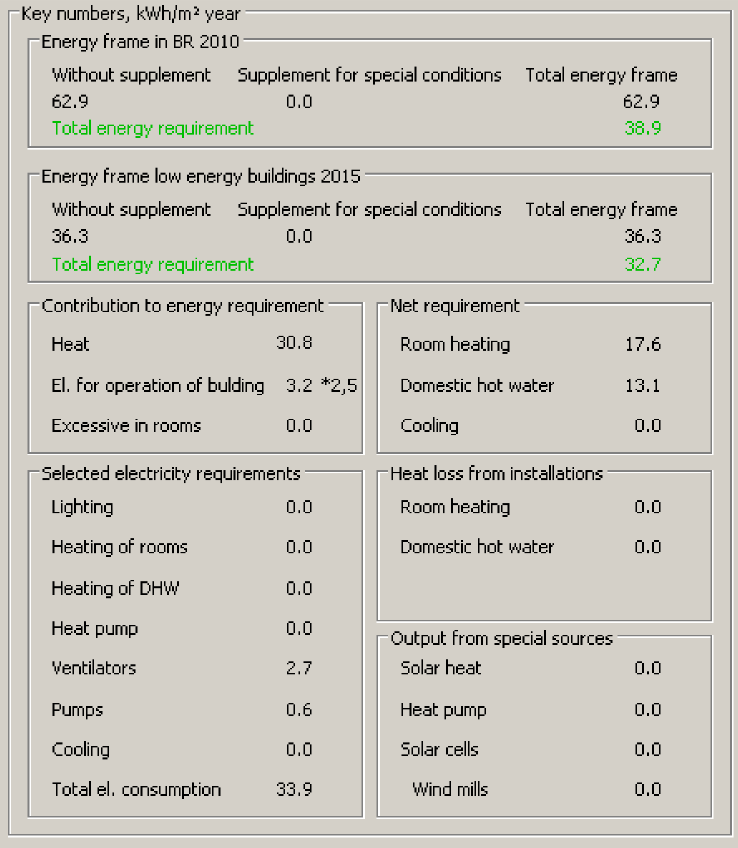


Figure 4 – LDV 159 house

Be 10 calculation – DLV 159

Figure 5 shows results of Be10 calculation of DLV159 house improved to class 2015.



Key numbers, kWh/m² year

Energy frame in BR 2010

Without supplement	Supplement for special conditions	Total energy frame
62.9	0.0	62.9
Total energy requirement		38.9

Energy frame low energy buildings 2015

Without supplement	Supplement for special conditions	Total energy frame
36.3	0.0	36.3
Total energy requirement		32.7

Contribution to energy requirement

Heat	30.8
El. for operation of bulding	3.2 *2,5
Excessive in rooms	0.0

Net requirement

Room heating	17.6
Domestic hot water	13.1
Cooling	0.0

Selected electricity requirements

Lighting	0.0
Heating of rooms	0.0
Heating of DHW	0.0
Heat pump	0.0
Ventilators	2.7
Pumps	0.6
Cooling	0.0
Total el. consumption	33.9

Heat loss from installations

Room heating	0.0
Domestic hot water	0.0

Output from special sources

Solar heat	0.0
Heat pump	0.0
Solar cells	0.0
Wind mills	0.0

Figure 5 – Be10 calculation of DLV 159 house improved to class 2015

Be10 doesn't support modelling of some building details (sloped roof, overhangs) in simple form and thus the IDA-ICE model was slightly simplified to fit the BE10 model. The UA value [W/K] of the house modelled in IDA-ICE was adjusted to be the same as in Be10, because IDA-ICE considering inner area of walls while Be10 outer area. Moreover the linear heat loss from building components was also adjusted to be the same. A SFP for ventilation system is 0.8kJ/m3 and power consumption of SH pump is 20W (running only during heating season).

Comparison of results from Be10 and IDA-ICE model for heating demand shown a maximal difference of 10% what is considered as a good accuracy (see Table 6).

Table 6 – comparison of space heating demand calculated by Be10 and IDA-ICE for simplified building shape

	Be10	IDA - ICE
Space Heating [kWh/a]	2816	2550*
demand [kWh/(m2.a)]	17.6	15.94*
Difference [%]	10	

* heat demand for IDA-ICE calibration case differs slightly from case "A RAD", referred later in the text, because of simplified geometry. The same explanation is applied also for the house 3B which is described in the next chapter.

3.1.2 Two-storey semi-detached single-family house type 3B

Single-family house type 3B represents an example of two-storey single-family house with 3 rooms and gross heated area 95m^2. The house is meant to be built as semi-detached or as a row house and thus external wall in the kitchen is considered as adiabatic wall because we are assuming room with the same temperature on the other side of the wall.

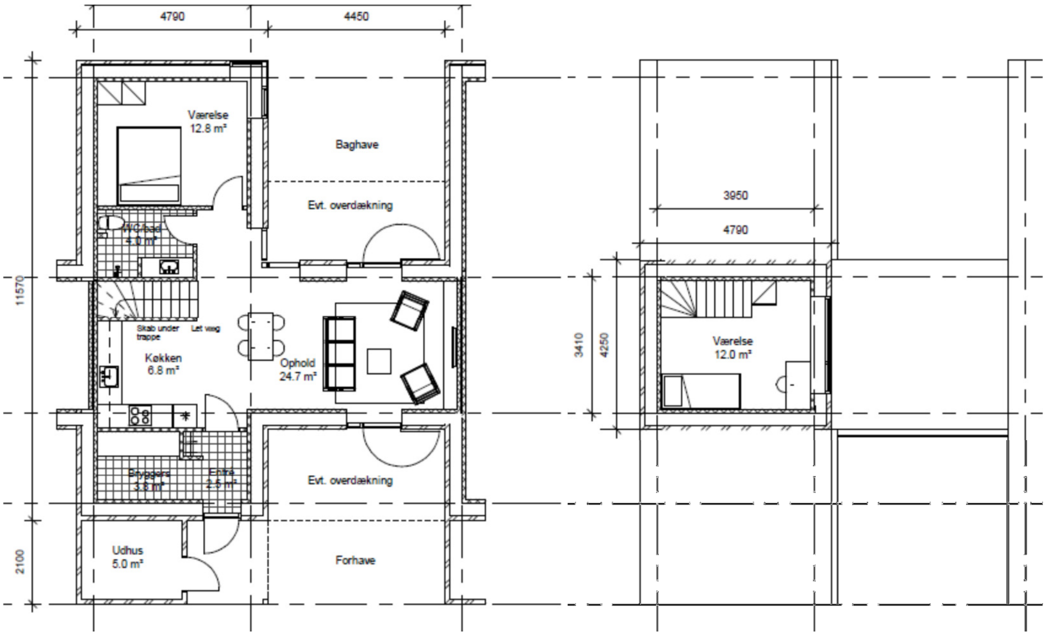
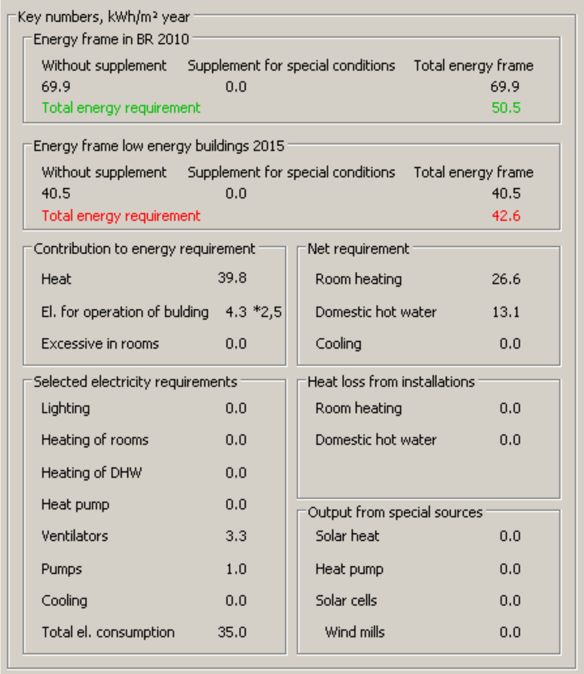


Figure 6 – ground plan of 3B house

Be 10 calculation – 3B house



Key numbers, kWh/m² year

Energy frame in BR 2010

Without supplement	Supplement for special conditions	Total energy frame
69.9	0.0	69.9
Total energy requirement		50.5

Energy frame low energy buildings 2015

Without supplement	Supplement for special conditions	Total energy frame
40.5	0.0	40.5
Total energy requirement		42.6

Contribution to energy requirement

Heat	39.8
El. for operation of bulding	4.3 *2,5
Excessive in rooms	0.0

Net requirement

Room heating	26.6
Domestic hot water	13.1
Cooling	0.0

Selected electricity requirements

Lighting	0.0
Heating of rooms	0.0
Heating of DHW	0.0
Heat pump	0.0
Ventilators	3.3
Pumps	1.0
Cooling	0.0
Total el. consumption	35.0

Heat loss from installations

Room heating	0.0
Domestic hot water	0.0

Output from special sources

Solar heat	0.0
Heat pump	0.0
Solar cells	0.0
Wind mills	0.0

Figure 7 - Be10 calculation of 3B house

Due to Be10 calculation, 3B house doesn't fulfilling requirements for class 2015 even has the same constructions as house DLV 159. Calculated energy demand is 42.6 kWh/(m2.a) while the energy frame is 40.5 kWh/(m2.a). The difference between the energy requirement and the calculated value is only 2.1 kWh/(m2.a), and it can be removed by use of more efficient HVAC system, e.g. fans. If more efficient fans with SFP 0.4 kJ/m3 instead of 0.8 kJ/m3 will be used, the annual energy demand will decrease to 38.5 kWh/(m2.a) which is in below the energy frame for class 2015. Ventilation units with SFP 0.4 kJ/m3 are commercially available, the question is if the price is acceptable .The power consumption of SH pump is 20 W (running only during heating season).

The main reason why 3B house doesn't fit the energy frame (with ventilation system with SFP 0.8 kJ/m3) is not "compact" design resulting in high ratio between area of external walls and heated area. It is mainly caused by room in first storey (four external walls) and room 12.8 in ground floor (three external walls and big windows). Moreover regarding comparison of energy frame calculation with house DLV159, house 3B has disadvantage of smaller heated area, which resulting in higher energy consumption for space heating circulation pump (1 vs. 0.6 kWh/(m2.a)) and ventilation (3.3 vs. 2.7 kWh/(m2.a)).

Comparison of results from Be10 and IDA-ICE model for heating demand shown a maximal difference of 3% what is considered as a good accuracy (see Table 7).

Table 7 – Be 10 calculation of 3B house

	Be10	IDA - ICE
Space Heating [kWh/a]	2527	2603
demand [kWh/(m2.a)]	26.6	27.4
Difference [%]	3*	

* heat demand for IDA-ICE calibration case differs slightly from case “A RAD”, referred later in the text, because of simplified geometry.

Results & discussion

Table 8 shows overview of energy demand and design maximal heating power needed for space heating and DHW for two simulated houses. The results of peak power are valid only for floor heating with defined composition of floor and control. The results are in more details described in following text and more data is also presented in appendix.

Table 8 – overview of results without and with application of primary energy factor

		95m^2 - 3 persons				**159m^2 - 4 persons**			
		case A RAD	**case A**	**case B**	**case C**	**case A RAD**	**case A**	**case B**	**case C**
excluding primary energy factor!	**energy demand for SH and DHW [kWh/a]**	3706	3808	6024	6977	4564	4647	7210	8919
	energy demand vs. case A [%]	97	100	158	183	98	100	155	192
	DHW [kWh/a]	1238	1238	2400	2400	2077	2077	3200	3200
	SH + AHU [kWh/a]	2468	2570	3624	4577	2487	2570	4010	5719
	peak power for systems [kW]								
	DHW [kW]	32.3*				32.3*			
	SH - floor heating + air heater [kW]	2.7	3.0	3.0	3.0	3.1	3.0	3.0	3.0
with primary factor for DH = 0.8	energy demand for SH and DHW [kWh/a]	2965	3047	4820	5582	3652	3718	5768	7135
	energy demand for SH and DHW [kWh/(m2.a)]	31.2	32.1	50.7	58.8	23.0	23.4	36.3	44.9
energy frame	energy frame BR10 - class 2015	40.5				36.3			
	energy available for HVAC operation, and heat loss from storage tank	9.3	8.5	-10.2	-18.2	13.3	12.9	0.0	-8.6
other demand	expected unrecoverable heat loss from developed DHW unit [kWh/(m2.a)]	4.4	4.4	3.9	3.5	2.8	2.8	2.4	2.2
	energy available for HVAC (pumps, fans) operation [kWh/(m2.a)]**	4.9	4.0	-14.1	-21.7	10.5	10.1	-2.4	-10.8

* value of 32.3kW for DHW is peak power needed on secondary side of substation, peak power from DH will be lower in case of using substation with buffer tank

** energy available for HVAC systems operation should be additionally divided by primary energy factor (for electricity recently 2.5) to get the max. allowed energy demand to fit the frame

3.2 Lind&Risor DLV 159

Heat demand duration curve

Figure 8 shows **space heating demand power curve** for individual cases. The basic case is case A with radiators controlled by P regulator based on air temperature. The curve in fact represent heat demand duration curve for indoor air temperature 20°C, because radiators reacts immediately (very short time constant) and P regulator ensures that heat emitted to the room is the same amount as needed (dead band is 0.5K). The same curve is plotted also for cases B and C.

Other curves represent space heating power duration curves for cases when the house is equipped with FH system with thermostat regulator, dT=3K and weather compensated regulation. The shape of the curves is discussed below.

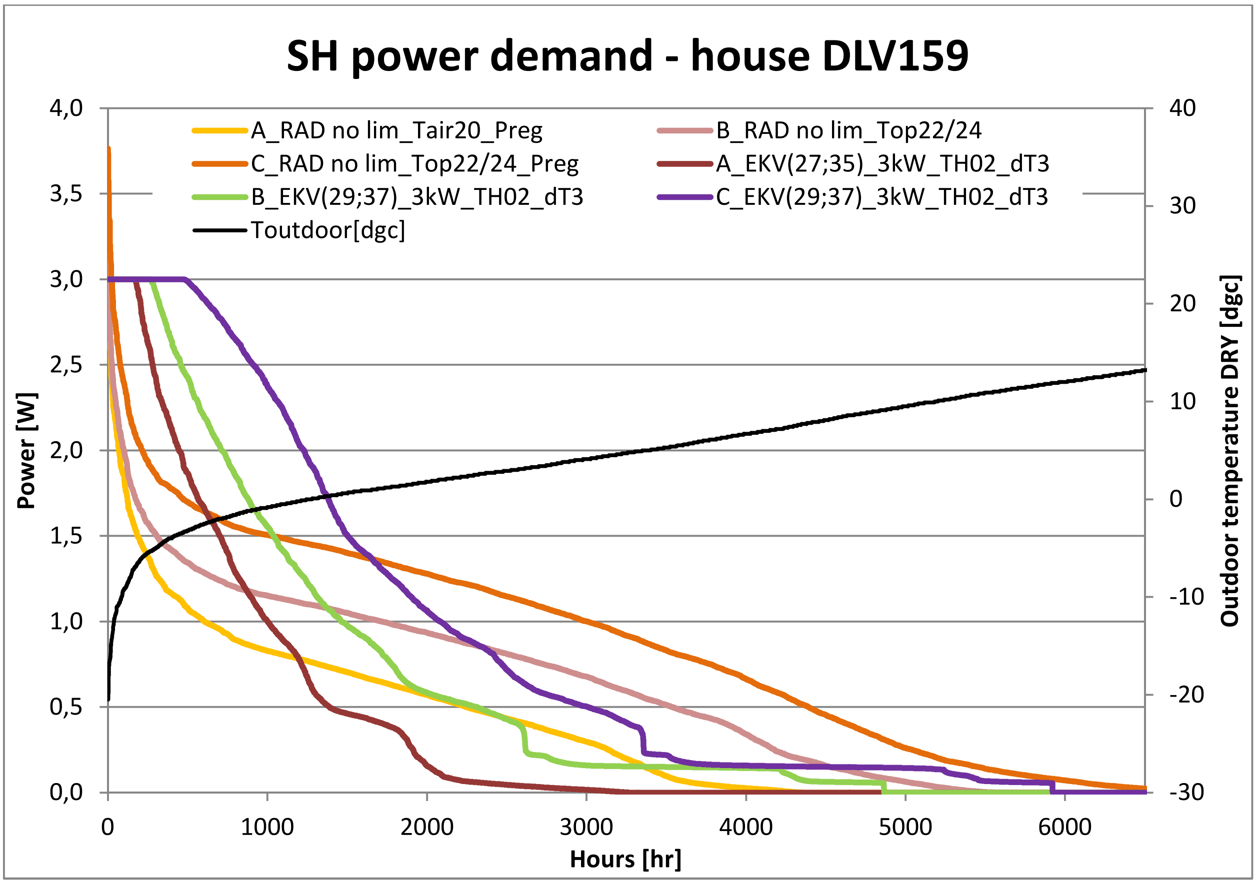


Figure 8 – heat load duration curve for space hating in DLV159, not includes DHW

Figure 8 shows also duration of heating season. It should be stressed, that the duration of heating period is valid only for curves expressing heat output from radiators. For curves representing FH it is number of hours when the FH system was in operation. The reason is while radiators are operated continuously a FH system is operated on/off. Sum of hours when RAD is operated is approximately 1000 hours shorter that time of operation of FH.

Floor heating

Different shape of curves

The different shapes of the curves will explained on results from case B.

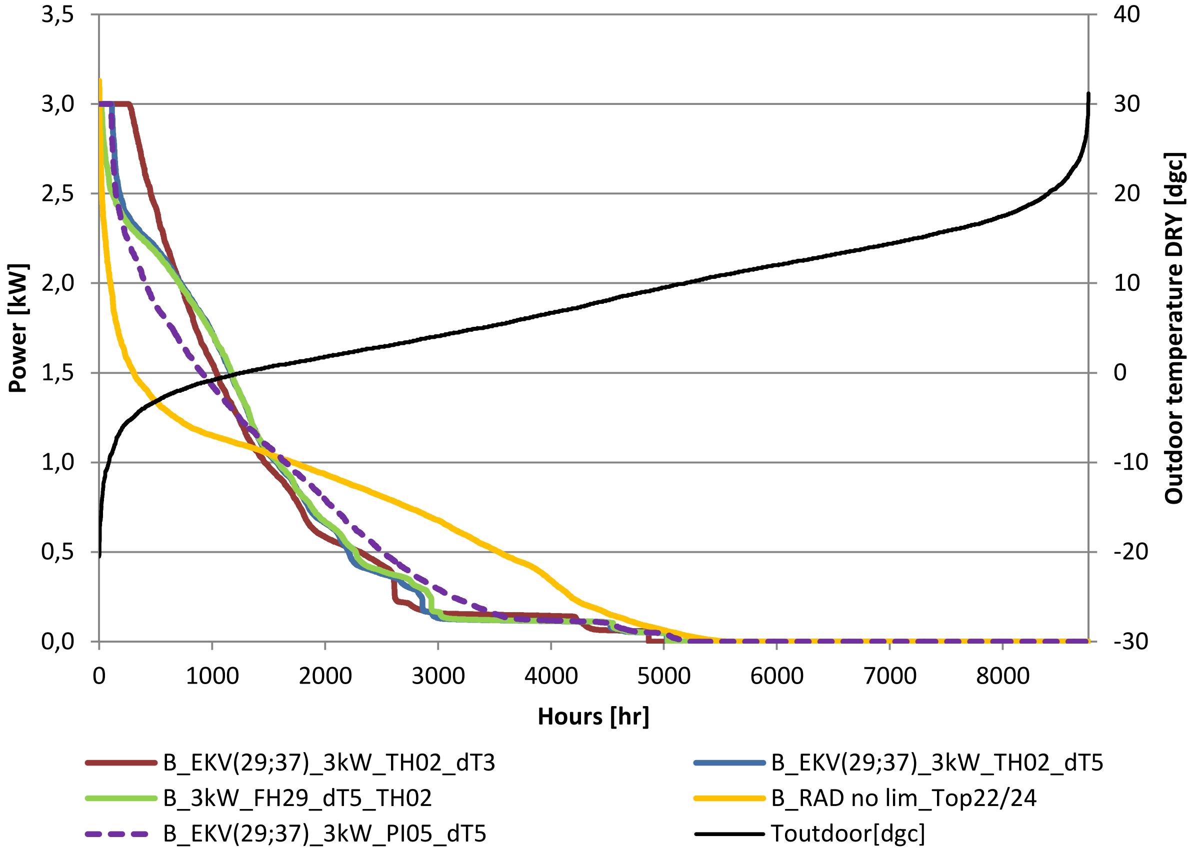


Figure 9 – heat load duration curves for space heating in house DLV 159 – explanation of different shapes

Thermostat vs. PI regulation 🟦 🟪

The violet dashed curve represents case of floor heating controlled by PI regulator with weather compensated supply temperature. In reality it means that FH can be controlled from zero power to maximum by change of supply temperature to each FH loop. It can be seen that the curve is monotonic and smooth. Anyway to implement such a control to reality will need step-valve or mixing loop for each individual FH loop and it will be expensive and basically without sense. A standard solution is one mixing loop for all FH loops which are equipped with on/off valves controlled by temperature sensors - thermostats in individual rooms. This solution doesn't allow control FH in real meaning, but only fully open or close valve. As a consequence the curves are no smooth anymore and have inflection points. The blue curve represents this solution (dead band on thermostat = 0.2 K). From perspective of occupant the main advantage of PI regulation is reduced number of hours with operative temperature below desired value (22°C) which can be seen in Table 9 (blue vs. violet line). Table 9 shows number of hours below desired value in room 11.9 which was chosen because represents a room with lowest operative temperature.

Weather compensated regulation vs. Constant temperature of supply water 🟦 🟩

There is almost no difference in heat demand curve between case with weather compensated regulation and constant temperature of supply water (blue vs. green curve), but there is a difference in thermal comfort for occupants. Solution with constant supply temperature has lower minimal operative temperature (21.33°C) while solution with weather compensated control has minimal operative temperature 21.54 and reduced number of hours with temperature below 21.9°C. Even the dT on the FH loop is still 5K for both systems, the heating medium differential temperature Θ (taking in consideration beside T_{sup} and T_{ret} also T_{indoor}) is higher and thus more heat from FH can be supplied into the room.

Design temperature difference on loop 5K vs. 3K 🟦 🟥

The curve (blue) for 5K design temperature difference has slightly different shape from curve with design difference temperature 3K (red). The 3K design has higher Θ and H coefficient (because flow rate is higher than in case of 5K) and it results faster dynamic and thus reduced number of hours below 22°C.

Table 9 – number of hours with operative temperature below desired value

room 11.9	hours below desired temperature (whole year)							
	tmin	21	21.4	21.6	21.8	21.9	21.95	22
B_EKV(29;37)_3kW_TH02_dT3	21.56	0	0	4	27	435	1131	1866
B_3kW_FH29_TH02_dT5	21.33	0	5	15	129	679	1368	2083
B_EKV(29;37)_3kW_TH02_dT5	21.54	0	0	5	49	657	1368	2090
B_RAD no lim_Top22/24	22.06	0	0	0	5	39	133	573
B_EKV(29;37)_3kW_PI05_dT5	21.54	0	0	5	49	308	907	2133

FH operation and return temperatures

The system is controlled on/off by room thermostat with dead band 0.2 K. Figure 10 shows supply/return temperatures from FH loop in room 11.6 for first week in January. Pink curve represents temperature of water available for supply of the loop. It can be seen that around hour 130 the temperature falls to 25°C. It is caused by limit of maximal power for SH and AHU heating to 3 kW and at that time FH system needs more power because of very low outdoor temperature (dashed curve-secondary axes). Even there is not enough power, operative temperature doesn't drop below 20°C. Green curve represents temperature of water supplied to the FH loop and azure curve represents temperature of water leaving from FH loop. The FH system in room 11.6 is in first week in January supplied with heating water roughly once a day (8 times) for period between 1 – 13 hours.

The weighted annual average temperature of water returning from FH loop of room 11.6 is 22.56°C, which is very good result. The overall average of FH return for whole house is 22.38°C.

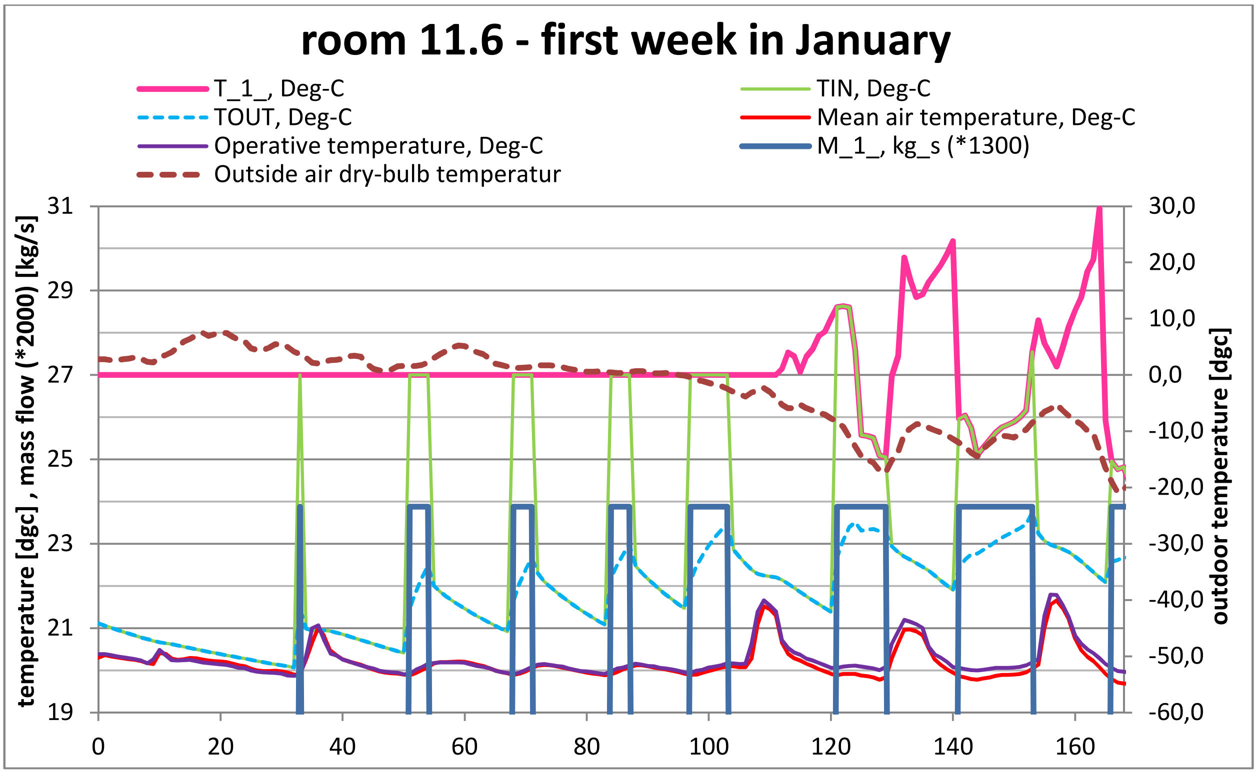


Figure 10 – detailed operating conditions of FH in room 11.6 – first week in January

Energy demand defined by BR10 vs. expected real demand

The difference in heat demand for SH and DHW between case A and B and case A and C (without accounting heat loss from DHW storage tank) is 2563 kWh/a and 4277 kWh/a and it corresponds to increase of energy demand by 55% and 92% in comparison with case A. For detailed values see Table 8.

Influence of peak power on thermal comfort in rooms

Low-energy houses has in general long time constant and thus peak power to space heating system can be very often considerably decreased without serious affecting of thermal comfort in the rooms and thus nominal power of heat source/DH connection can be reduced. In case of floor heating a situation is even more favourable than in case of radiators because the thermal capacity of the floor is increased by composition and higher temperature. In addition, peak outdoor temperatures occurs rarely and last usually for short period and thus short reduction in indoor temperature cannot be seen as problem. Figure 11 shows minimal operative temperature for all rooms (see Table 10 for room identification).

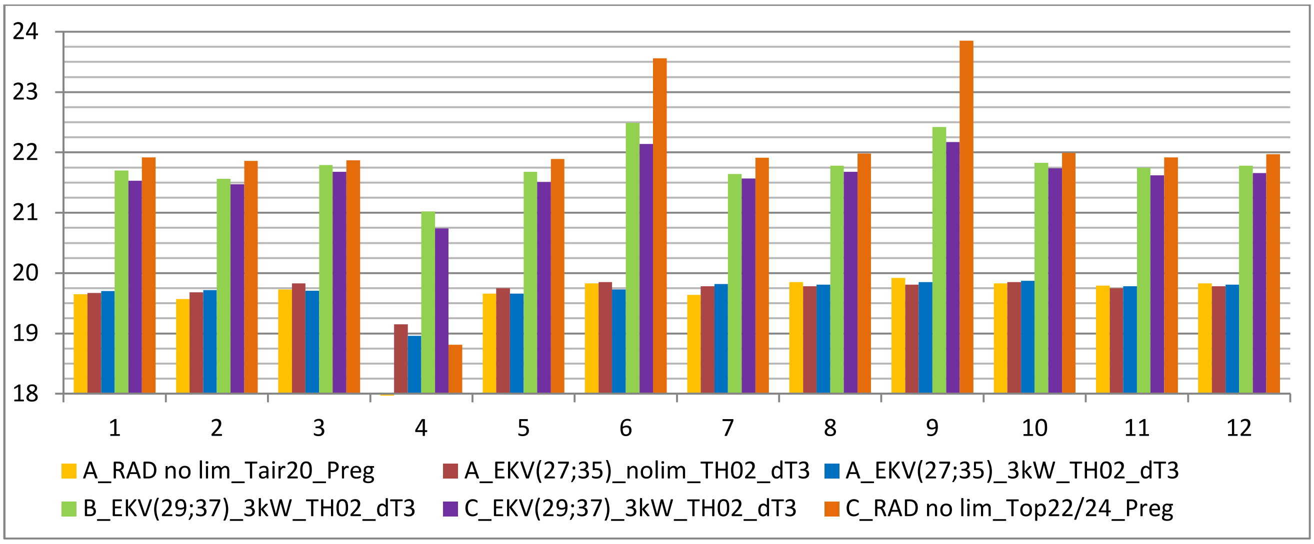


Figure 11 – minimal operative temperature in individual rooms, house DLV159

Table 10 – list of rooms in DLV159 house

#	room	#	room	#	room	#	room
1	Vaerelse 11.6	4	Entre 4.1	7	Sovevaerelse 15.0	10	Gang 2.6
2	Vaerelse 11.9	5	Vaerelse 9.1	8	Kokken 9.4	11	Stue 32.0
3	Bryggers 9.1	6	Bad 1 8.3	9	Bad 2 4.3	12	Alrum 20.1

It can be seen that room with lowest temperature is room number 2, i.e. room 11.9 (entre is not considered a room with need high thermal comfort). Table 11 shows hours below desired temperature in room 11.9. The number of hours in range 19.9 – 20.0 and 21.9-22.0 can't be seen as a real problem because it is only mathematical definition of desired values and occupants are anyway not able to feel difference smaller than 0.1 K

Table 11 – hours below desired operative temperature in room 11.9

room 11.9 - hours below desired temperature								
	case A							
	t_{op} min	19.4	19.5	19.7	19.8	19.9	19.95	20
A_RAD no lim_Tair20_P-reg	19.57	0	0	204	1153	2938	3399	3787
A_EKV(27;35)_nolim_TH02_dT3	19.78	0	0	0	1	259	672	1238
A_EKV(27;35)_3kW_TH02_dT3	19.72	0	0	0	6	269	726	1336
	case B and C							
	t_{op} min	21	21.4	21.6	21.8	21.9	21.95	22
B_EKV(29;37)_3kW_TH02_dT3	21.56	0	0	4	27	435	1131	1866
C_EKV(29;37)_3kW_TH02_dT3	21.46	0	0	11	80	678	1518	2352
C_RAD no lim_Top22/24_P-reg	21.86	0	0	0	0	7	61	441

Case A

The amount of hours below desired temperature for case A – radiators (T_{AIR}=20°C) is a lot. It is caused by the fact that radiators are in this case controlled by P-controller sensing air temperature. The air temperature (data not shown) is below 19.95°C only 7 hours. Small amount of hours with T_{AIR} below 19.95°C is caused by precise control and fast reaction of radiators. A floor heating system has much higher time constant and thus is not able to react enough fast on fast changes in outdoor temperature. The consequence is much higher number of hours below desired temperature. Nevertheless major part of hours is above 19.8°C of operative temperature.

The easy solution will be increase slightly set-point, e.g. 0.2°C. In this way, the floor will accumulate more heat and number of hours below 20°C will be reduced. On the other hand, the energy demand for the space heating will increase.

Case B and C

Case B has around 1100 hours below temperature level 21.95°C, but this value can't be seen as relevant, because thermostat has dead band 0.2 K, i.e. FH is started when operative temperature in room drops below 21.9°C. A number of hours with Top below 21.9°C is only 27, i.e. 0.57% for heating period of 4774 hours per year (for desired temperature 22°C).

The results for case C are similar to B, but the minimal operative temperature is lower and amount of hours below desired temperature is longer. The reason is internal heat gains reduced to 3W/m2 from original 5W/m2 applied in case B while the design of FH system was the same.

Influence of heat loss from DH substation on energy demand for space heating

Moreover we also investigated how much of heat loss from DH substation can be recovered for case when house is equipped with DH substation with storage tank, with heat loss of 96 or 90W (corresponding to UA value 3W/K). House has ventilation system with heat recovery (efficiency 85%) and thus heat lost from the DH substation can be to some extent used for reduction of heat demand for space heating.

It can be seen that in case A heat loss from DH substation is approximately 841kWh/a (see Table 12) and 34% of the heat loss is recovered for space heating. For cases B and C, the heat loss from substation decrease to 788kWh/a (because of decreased temperature difference between substation and indoor temperature) and amount of recovered heat is 39% and 45% for case B and C respectively.

Table 12 – heat recovered from DHW storage tank

	approx. heat loss from DHSU [kWh/a]	heat loss **USED** for SH [kWh/a]	heat loss used for SH [%]	heat loss **NOT** used for SH [kWh/a]	extra loss incl. Prim factor 0.8 [kWh/(m2.a)]
Case A (heat loss 96W)	841	287	34	554	2.8
Case B (heat loss 90W)	788	309	39	480	2.4
Case C (heat loss 90W)	788	357	45	431	2.2

Conclusion

Based on the presented results we chose 3kW as the optimal design peak power for space heating of house DLV 159.

3.3 Semi-detached house 3B

Heat demand duration curve

Figure 8 shows **space heating demand power curve** for individual cases. The basic case is case A with radiators controlled by P regulator based on air temperature. The curve in fact represent heat demand duration curve for indoor air temperature 20°C, because radiators reacts immediately (very short time constant) and P regulator ensures that heat emitted to the room is the same amount as needed (dead band is 0.5K). The same curve is plotted also for cases B and C.

Other curves represent space heating power duration curve for cases when the house is equipped with FH system with thermostat regulator, dT=3K and weather compensated regulation.

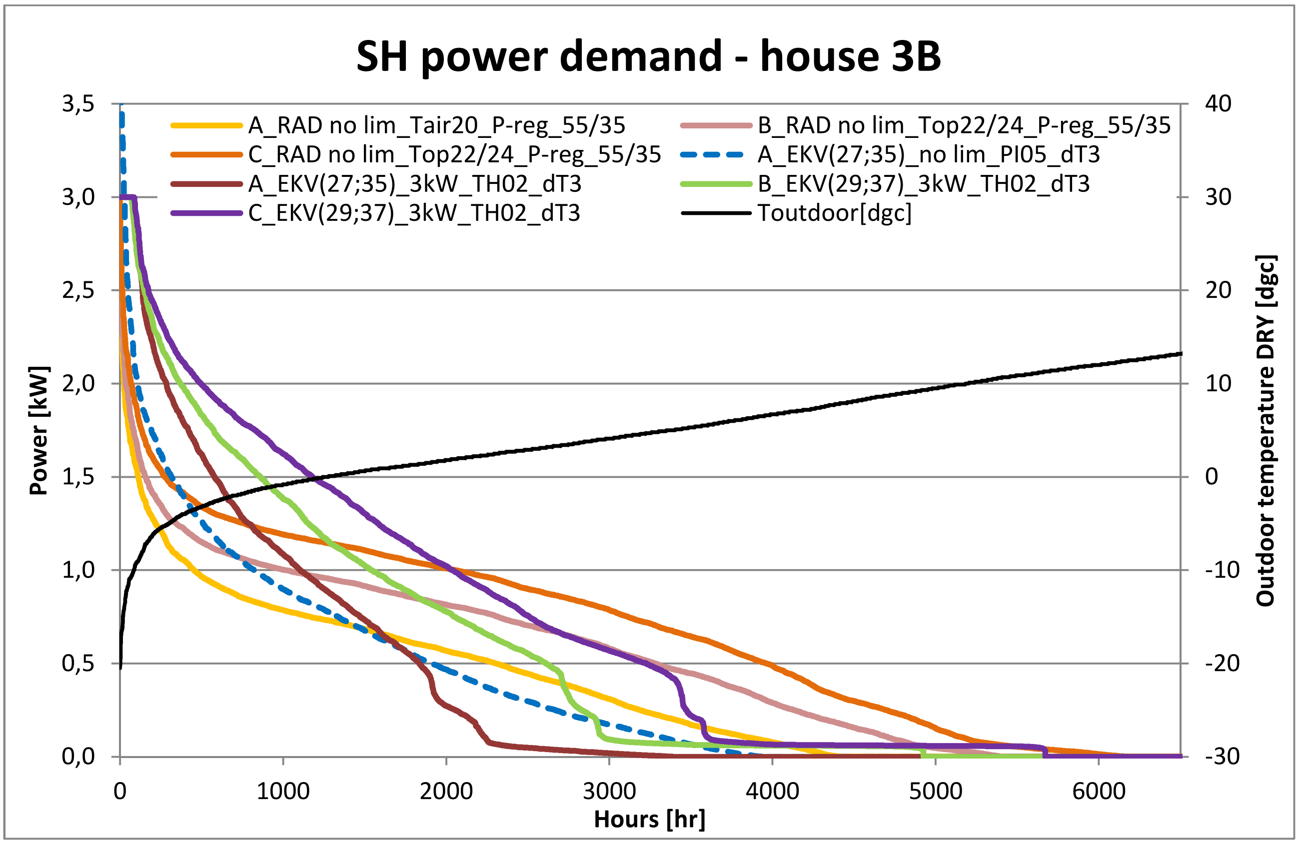


Figure 12 - heat load duration curve for space heating in house 3B, not including DHW

Floor heating

The design of floor heating is the same as for house DLV159. All information regarding shape of curves are described in previous chapter.

Energy demand defined by BR10 vs. expected real demand

The difference in heat demand for SH and DHW between case A and B and case A and C (without accounting heat loss from DHW storage tank) is 2216kWh/a and 3169kWh/a and it corresponds to increase of energy demand by 58% and 83% in comparison with case A. For detailed values see Table 8.

Influence of peak power on thermal comfort in rooms

Figure 13 shows minimal operative temperature for all rooms (see Table 13 for rooms identification).

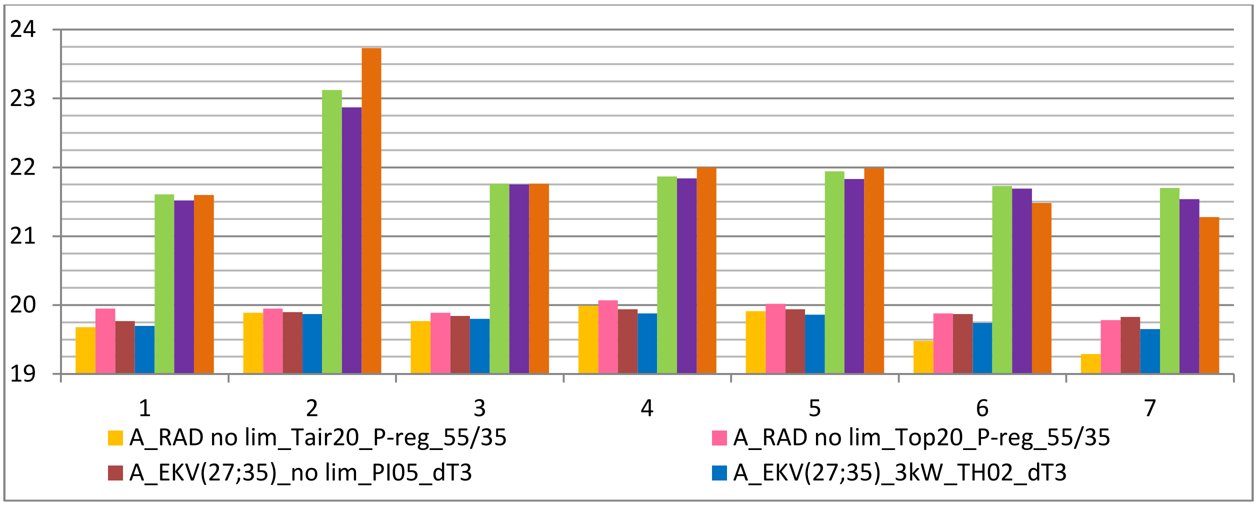


Figure 13 – minimal operative temperature in individual rooms, house 3B

Table 13 – list of rooms in house 3B

#	room	#	room	#	room
1	bryggers entre 6.3m2	4	kokken 6.8m2	7	room 12.8
2	WC/bad 4m2	5	stairs		
3	ophold 24.7m2	6	top_room		

Based n the results of case A with radiators, the coldest room in the house is room 12.8. Table 14 shows hours below desired temperature in room 12.8. The number of hours in range 19.9 – 20.0 and 21.9-22.0 can't be seen as a real problem because it is only mathematical definition of desired values and occupants are anyway not able to feel difference smaller than 0.1 K

Table 14 – hours below desired operative temperature in room 12.8

room 12.8 - hours below desired temperature

case A

	top min	19.4	19.5	19.7	19.8	19.9	19.95	20
A_RAD no lim_Tair20_P-reg_55/35	19.29	25	224	1837	2736	3468	3782	3948
A_RAD no lim_Top20_P-reg_55/35	19.78	0	0	0	2	17	89	409
A_EKV(27;35)_no lim_TH02_dT3	19.80	0	0	0	1	321	850	1348
A_EKV(27;35)_3kW_TH02_dT3	19.65	0	0	3	10	320	837	1348

case B and C

	top min	21	21.4	21.6	21.8	21.9	21.95	22
B_EKV(29;37)_3kW_TH02_dT3	21.70	0	0	0	13	484	1048	1685
C_EKV(29;37)_3kW_TH02_dT3	21.54	0	0	3	20	576	1201	1877
C_RAD no lim_Tair0_P-reg_55/35	21.28	0	43	1105	2925	3787	4017	4232

Case A

The amount of hours with operative temperature below 20°C is in case A-radiators (yellow row) rather big. The reason is, that radiator was controlled by P-controller (dead band 0.5) for T_{air}, what is the case of standard controllers. If the sensor for operative temperature is applied, number of hours bellow 20°C will we vanished (pink row).

The influence of peak power limitation to 3 kW can be seen from comparison of red and blue row. Limitation to 3 kW slightly decreased minimal operative temperature (19.8°C -> 19.65°C) and increase number of hours below 19.8°C, but it can't be seen as an important decrease in thermal comfort. The peak power in unlimited case was 6 kW, i.e. that we decreased needed maximal heat demand power to 3 kW, i.e. one half.

Case B and C

A number of hours with temperature below desired level is in case B and C little higher than in case A. It is caused by the fact that the design of FH system remains the same while temperature set-point was increased to 22°C. Moreover in case C the internal heat gains are reduced to 3W/m2 which leads to lower minimal temperature and further increase of number of hours. Anyway, it should be said that even there are some hours below desired temperature, the lowest temperature is 21.54°C which should be still seen as high comfort.

For case C-radiators applies the same explanation as for case A-radiators.

Influence of heat loss from DH substation on energy demand for space heating

In case A heat loss from DH substation is approximately 841kWh/a (see Table 15) and 38% of the heat loss is recovered for space heating. For case B and C, the heat loss from substation decrease to 788kWh/a and amount of recovered heat is 41% and 48% for case B and C respectively.

Table 15 – heat loss recovered from DHW storage tank

	approx. heat loss from DHSU [kWh/a]	heat loss **USED** for SH [kWh/a]	heat loss used for SH [%]	heat loss **NOT** used for SH [kWh/a]	extra loss incl. Prim factor 0.8 [kWh/(m2.a)]
Case A (heat loss 96W)	841	316	38	525	4.4
Case B (heat loss 90W)	788	322	41	466	3.9
Case C (heat loss 90W)	788	377	48	411	3.5

Conclusion

Based on the presented results we chose 3kW as the optimal design peak power for space heating of house 3B.

4 References

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5 Appendix

5.1 Common values for both buildings

Table 16 – DH substation for DHW and AHU

DHSU HEAT LOSS (t_{avg}-t_{air})*UA_{DHSU}	
heat loss coefficient [W/K]	3
t_{avg} DHSU [dgc] (55+47)/2 "8 dgc difference between top and 1/3 as in Lystrup"	52
heat loss for t_{air} 20dgc [W]	96
heat loss for t_{air} 22dgc [W]	90

AHU
heat recovery 85%
heating - water heater supplied by DH, efficiency 100%
t_{supply} air = 18dgc (unit without cooling coil)

*model doesn't account for heat loss from DHW pipes

Table 17 – space heating control and floor heating composition

SPACE HEATING - Floor heating

control		composition	
t_{air}= 20°C	$t_{operative}$= 22°C (24°C in bathroom)	temperature drop on one loop [K]	3
Dead band for P and PI controller =0.5 K		$t_{surface}$ design max [dgc]	27
Dead band for Thermostat = 0.2 K		depth pipe axes from the floor [m]	0.08
		heat transfer coefficient in accordance with EN 15377-1	15*

* H values for house DLV 159: top-room = 28.01 W/m^{2}K , room 12.8 = 37.07W/m^{2}K

5.2 DLV 159

5.2.1 Results

Table 18 – the peak power and heat demand for house DLV 159 re-designed to fulfil class 2015

RESULTS - DLV 159

frame 2015 **36.3** kWh/(m2.a)

area [m2] **159**

		P_{max} [W]	delivered energy SH + AHU [kWh/a] 1)	heat floor heating [kWh/a]	SH/area	AHU heater [kWh/a]	AHU heater/ area	DHW [kWh/a]	DHW /area	heatloss from storage tank [kWh/a]	total without prim. fact 2)[kWh/a]	total incl. prim. fact 2)[kWh/a]	total2) /area [kWh/(m2.a)]
no DHSU	A _HG5_Tair20_RAD	3137	2487	2142	13.5	346	2.2	2077	13.1	0	4564	3652	23.0
	A _HG5_Tair20	3000	2570	2225	14.0	346	2.2	2077	13.1	0	4647	3718	23.4
	B_ HG5_Top2224	3000	4010	3884	24.4	126	0.8	3200	20.1	0	7210	5768	36.3
	C_ HG3_Top2224	3000	5719	5587	35.1	133	0.8	3200	20.1	0	8919	7135	44.9
with DHSU	A_ HG5_Tair20	3000	2283	1996	12.6	287	1.8	2077	13.1	841	5201	4161	26.2
	B_ HG5_Top2224	3000	3702	3583	22.5	119	0.7	3200	20.1	788	7690	6152	38.7
	C_ HG3_Top2224	3000	5362	5235	32.9	127	0.8	3200	20.1	788	9350	7480	47.0

prim. Factor SH - FH	0.8
prim factor AHU heater	0.8
prim. Factor DHW	0.8

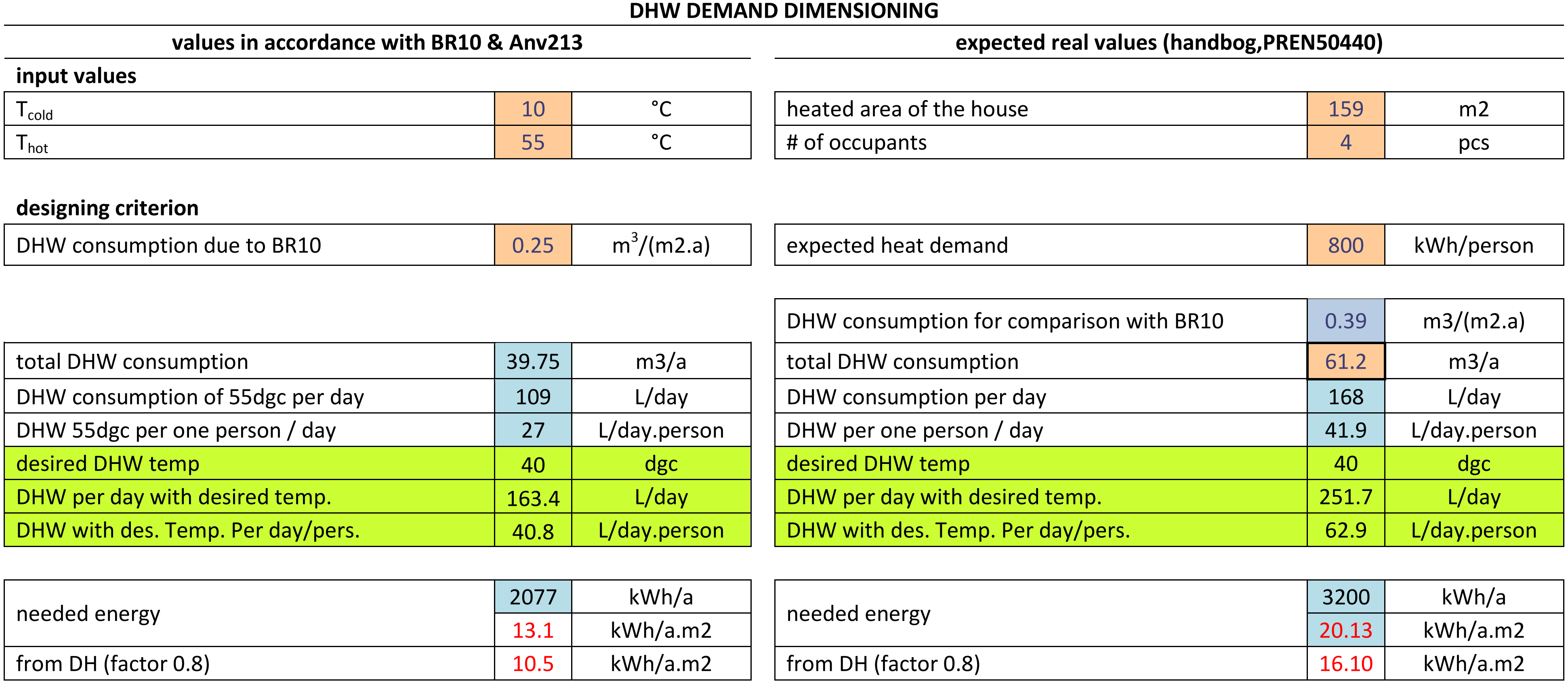
1) - includes also heat loss from storage tank

2) - without electricity for HVAC

5.2.2 Systems

5.2.2.1 *Energy demand for DHW*

Table 19 – calculation of DHW demand for DLV 159 house



DHW DEMAND DIMENSIONING

values in accordance with BR10 & Anv213			expected real values (handbog,PREN50440)		
input values					
T_{cold}	10	°C	heated area of the house	159	m2
T_{hot}	55	°C	# of occupants	4	pcs
designing criterion					
DHW consumption due to BR10	0.25	$m^3/(m2.a)$	expected heat demand	800	kWh/person
			DHW consumption for comparison with BR10	0.39	m3/(m2.a)
total DHW consumption	39.75	m3/a	total DHW consumption	61.2	m3/a
DHW consumption of 55dgc per day	109	L/day	DHW consumption per day	168	L/day
DHW 55dgc per one person / day	27	L/day.person	DHW per one person / day	41.9	L/day.person
desired DHW temp	40	dgc	desired DHW temp	40	dgc
DHW per day with desired temp.	163.4	L/day	DHW per day with desired temp.	251.7	L/day
DHW with des. Temp. Per day/pers.	40.8	L/day.person	DHW with des. Temp. Per day/pers.	62.9	L/day.person
needed energy	2077	kWh/a	needed energy	3200	kWh/a
	13.1	kWh/a.m2		20.13	kWh/a.m2
from DH (factor 0.8)	10.5	kWh/a.m2	from DH (factor 0.8)	16.10	kWh/a.m2

5.2.2.2 *Ventilation*

Table 20 – design of ventilation system for DLV 159 house

VENTILATION

desing due to BR10, chapter 6.3.1.2 - needed: 20L/s kitchen, 15L/s WC&shower, 10L/s bryggers

room	area [m^2]	# people	flow [L/s]	flow [L*s/m2]	height of room [m]	ACH [h-1]	flow m3/h
vaerelse	11.9	1	7	0.59	2.44	0.87	25.2
kokken	9.4	-	**20**	2.13	2.44	3.14	72
alrum	20.1	-	**10**	0.50	2.44	0.73	36
stue	32.0	-	**15**	0.47	2.44	0.69	54
sovevaerelse	15.0	2	**14**	0.93	2.44	1.38	50.4
WC/bad	8.3	-	**15**	1.81	2.44	2.67	54
vaerelse	9.1	-	**7**	0.77	2.44	1.13	25.2
entre	4.1	-	**0**	0.00	2.44	0.00	0
bryggers	9.1	-	**10**	1.10	2.44	1.62	36
vaerelse	11.6	1	**7**	0.60	2.44	0.89	25.2
WC/bad	4.3	-	**15**	3.49	2.44	5.15	-54
gang	2.6	-	**0**	0.00	2.44	0.00	0
summ	137.5	m2			ACH average	0.64	h-1

sum supply	60	L/s	216	m3/h
sum exhaust	-60	L/s	-216	m3/h

5.2.2.3 *Construction elements*

Table 21 – list of constructions used in DLV 159 house

CONSTRUCTIONS

windows - low energy			
solar heat gain coef.	0.46	$U_{glazing}$	0.9
T, solar transmitance	0.38	U_{frame}	0.9
Tvis, visible transmitance	0.65	internal/external emissivity	0.837/0.837

external walls (from inside)	thickness [m]	λ[W/m]	ro [kg/m3]	cp[kJ/kg]
concrete	0.1	1.7	2400	880
light insulation	0.4	0.034	20	750
air in 20 mm vert. Air gap	0.02	0.11*	1.2	1006
brick	0.11	0.58	1500	840
total thickness [m]	0.63			
total U value [W/m2K]	0.08087			
*Air in vertical gap, 20 mm, non-metallic surfaces, Tmean=10 Deg-C, Tdiff= 5.6 Deg-C, source: ASHRAE HF				
internal walls				
YTONG P2-500	0.1	0.39	1.2	1006
total U value [W/m2K]	1.258			
ceiling				
light insulation	0.5	0.14	500	2300
filigraan ceiling	0.18	1.7	2300	880
total thickness [m]	0.68			
total U value [W/m2K]	0.0706			
external floor (ground deck)				
wood	0.015	0.18	1100	920
screed	0.015	1.2	2000	750
concrete	0.1	1.9	2400	880
insulation	0.5	0.034	20	750
total thickness [m]	0.63			
total U value [W/m2K]	0.08212			
roof - concrete tiles				
concrete	0.02	1.7	2300	880
total U value [W/m2K]	5.502			

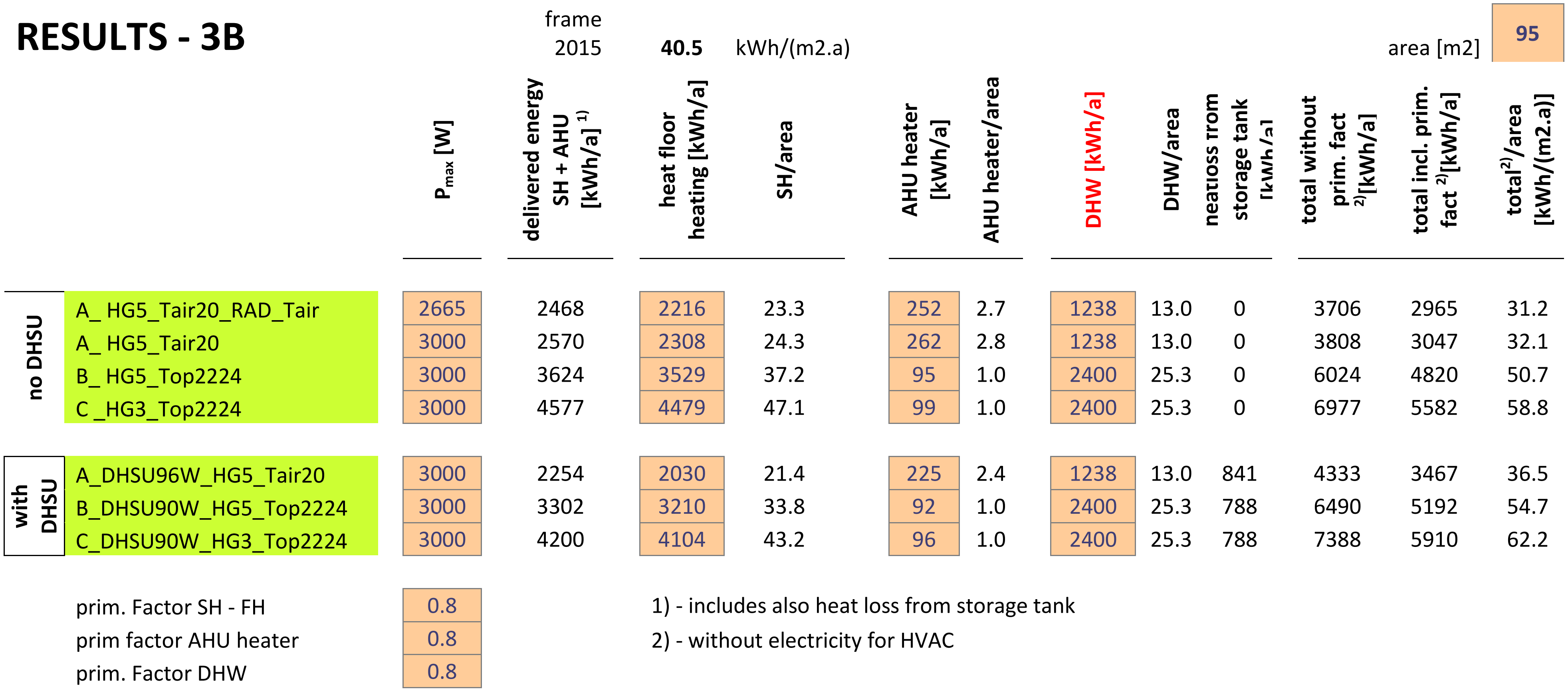
THERMAL BRIDGES	Ψ [W/m.K]
fundaments	0.1
joints between walls - windows and doors	0.02

5.3 Semi-detached house 3B

5.3.1 Results

The peak power and energy demand for semi-detached house type 3B are listed in Table 22.

Table 22 – the peak power and heat demand for house 3B



RESULTS - 3B

frame 2015 **40.5** kWh/(m2.a)

area [m2] **95**

		P_{max} [W]	delivered energy SH + AHU [kWh/a] 1)	heat floor heating [kWh/a]	SH/area	AHU heater [kWh/a]	AHU heater/area	DHW [kWh/a]	DHW/area	heatloss from storage tank [kWh/a]	total without prim. fact 2)[kWh/a]	total incl. prim. fact 2)[kWh/a]	total2)/area [kWh/(m2.a)]
no DHSU	A_ HG5_Tair20_RAD_Tair	2665	2468	2216	23.3	252	2.7	1238	13.0	0	3706	2965	31.2
	A_ HG5_Tair20	3000	2570	2308	24.3	262	2.8	1238	13.0	0	3808	3047	32.1
	B_ HG5_Top2224	3000	3624	3529	37.2	95	1.0	2400	25.3	0	6024	4820	50.7
	C _HG3_Top2224	3000	4577	4479	47.1	99	1.0	2400	25.3	0	6977	5582	58.8
with DHSU	A_DHSU96W_HG5_Tair20	3000	2254	2030	21.4	225	2.4	1238	13.0	841	4333	3467	36.5
	B_DHSU90W_HG5_Top2224	3000	3302	3210	33.8	92	1.0	2400	25.3	788	6490	5192	54.7
	C_DHSU90W_HG3_Top2224	3000	4200	4104	43.2	96	1.0	2400	25.3	788	7388	5910	62.2

prim. Factor SH - FH	0.8
prim factor AHU heater	0.8
prim. Factor DHW	0.8

1) - includes also heat loss from storage tank

2) - without electricity for HVAC

5.3.2 Systems

5.3.2.1 Energy demand for DHW

Table 23 - calculation of DHW demand for 3B house

DHW DEMAND DIMENSIONING

values in accordance with BR10 & Anv213

input values

T_{cold}	10	°C
T_{hot}	55	°C

designing criterion

DHW consumption due to BR10	0.25	$m^3/(m2.a)$

total DHW consumption	23.7	m3/a
DHW consumption of 55dgc per day	65	L/day
DHW 55dgc per one person / day	22	L/day.person
desired DHW temp	40	dgc
DHW per day with desired temp.	97.4	L/day
DHW with des. Temp. Per day/pers.	32.5	L/day.person

needed energy	1238	kWh/a
	13.1	kWh/a.m2
from DH (factor 0.8)	10.5	kWh/a.m2

expected real values (handbog,PREN50440)

heated area of the house	94.8	m2
# of occupants	3	pcs

expected heat demand	800	kWh/person

DHW consumption for comparison with BR10	0.48	m3/(m2.a)
total DHW consumption	45.9	m3/a
DHW consumption per day	126	L/day
DHW per one person / day	41.9	L/day.person
desired DHW temp	40	dgc
DHW per day with desired temp.	188.8	L/day
DHW with des. Temp. Per day/pers.	62.9	L/day.person

needed energy	2400	kWh/a
	25.32	kWh/a.m2
from DH (factor 0.8)	20.25	kWh/a.m2

5.3.2.2 Ventilation

Table 24 - design of ventilation system for 3B house

VENTILATION

designed due to BR10, chapter 6.3.1.2 - needed: 20L/s kitchen, 15L/s WC & shower, 10L/s bryggers

room	area [m^2]	# people	flow [L/s]	flow [L*s/m2]	height of room [m]	ACH [h-1]	flow m3/h
ophold	24.7	3	24	0.97	2.52	1.39	86.4
kokken	6.8	-	**20**	2.94	2.52	4.20	72
bryggers + entre	6.3	-	**10**	1.59	2.52	2.27	36
WC/bad	4	-	**15**	3.75	2.52	5.36	-54
varelse (12.8m2)	12.8	2	14	1.09	2.52	1.56	50.4
varelse 2nd floor (top room)	12	1	7	0.58	2.52	0.83	25.2
summ	66.6	m^2			ACH average	0.97	h-1

sum supply	45	L/s	162	m3/h
sum exhaust	-45	L/s	-162	m3/h

5.3.2.3 Construction elements

Table 25 - list of constructions used in DLV 159 house

CONSTRUCTIONS

windows - low energy - triple glazed				
solar heat gain coef.	0.5		$U_{glazing}$	0.9
T, solar transmitance	0.38		U_{frame}	0.9
Tvis, visible transmitance	0.65		internal/external emissivity	0.837/0.837
external walls (from inside)	thickness [m]	λ[W/m]	ro [kg/m3]	cp[kJ/kg]
concrete	0.1	1.7	2400	880
insulation	0.3	0.034	20	750
air gap	0.02	0.11*	1.2	1006
bricks	0.11	0.58	1500	840
total thickness [m]	0.53			
total U value [W/m2K]	0.1061			
*Air in vertical gap, 20 mm, non-metallic surfaces, Tmean=10 Deg-C, Tdiff= 5.6 Deg-C, source: ASHRAE HF				
internal walls				
YTONG P2-500	0.1	0.16	500	1000
total U value [W/m2K]	1.258			
internal floor (ceiling between floors)				
wood	0.015	0.14	500	2300
screed	0.015	1.2	2000	750
filigraan ceiling	0.18	1.7	2300	880
total thickness [m]	0.21			
total U value [W/m2K]	2.528			
external floor (terrændæk)				
wood	0.015	0.14	500	2300
screed	0.015	1.2	2000	750
concrete	0.1	1.9	2400	880
insulation	0.5	0.034	20	750
total thickness [m]	0.63			
total U value [W/m2K]	0.06656			
roof				
insulation	0.4	0.036	20	750
filigraan ceiling	0.18	1.7	2300	880
total thickness [m]	0.58			
total U value [W/m2K]	0.08782			
THERMAL BRIDGES			Ψ [W/m.K]	
fundaments			0.1	
joints between walls - windows and doors			0.02	