Ecodesign preparatory review study
Household Refrigeration

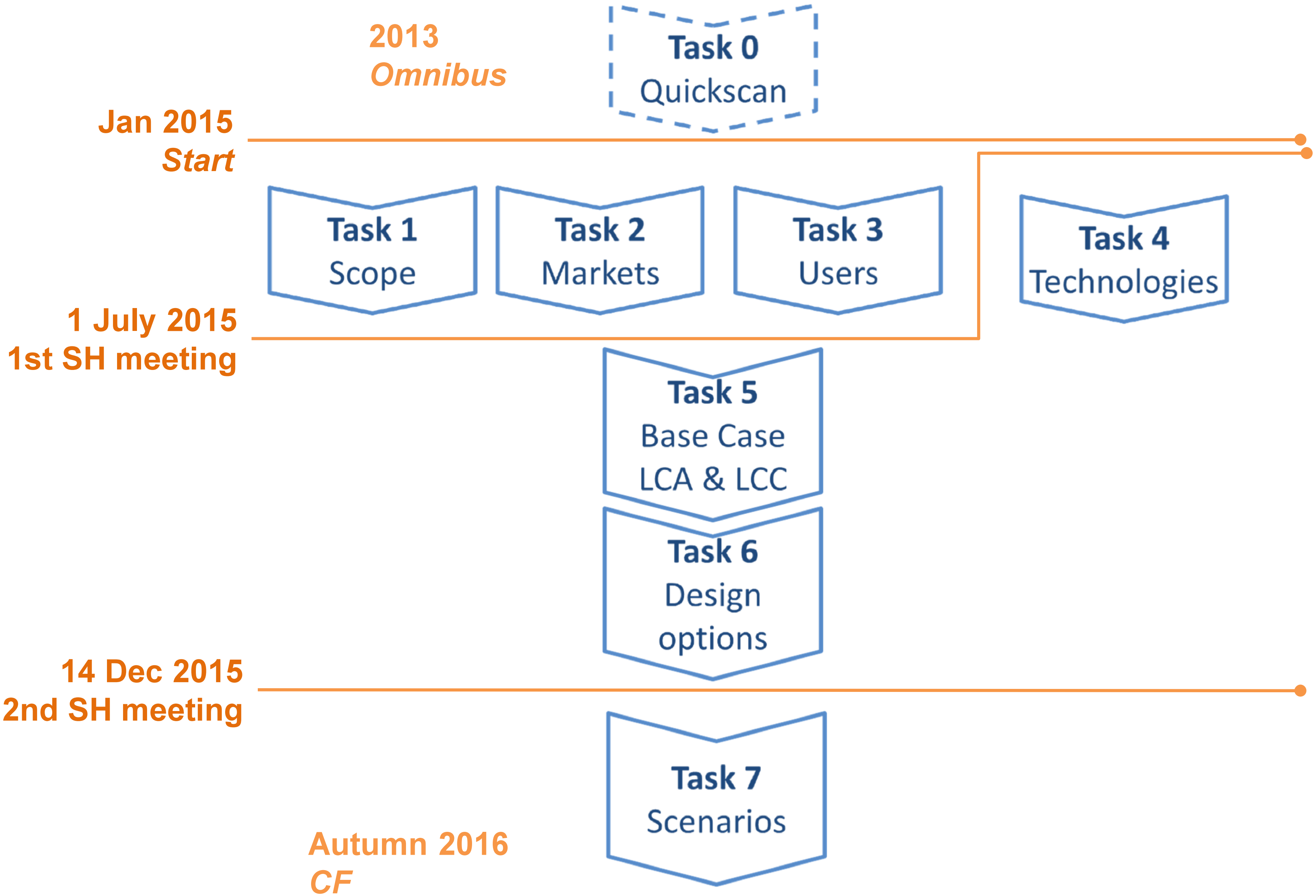
Ecodesign Stakeholder meeting
Brussels, 14 December 2015

Presented by
René Kemna (VHK)

Draft Agenda

- **9.30h registration**
- **10.00 meeting**
  - Changes in Task 1, 2, 3 (Ch. 3-7)
  - Task 4 (Ch. 8 & 9)
- **12.30-13.30h lunch**
  - Task 4 (Ch. 9 & 10)
  - Task 5 (Ch. 11)
  - Task 6 (Ch. 12)
  - AOB
- **End of meeting 16.00-18.00h**

Project Structure & Stakeholder involvement



Ch. 3 changes: Scope [task 1.1]

1. Keep non-household (minibar, wine cooler) in scope [Art. 1]
2. Use IEC definitions for appliance, (sub)compartment [Art. 2]
3. Use design/nominal/extreme temperatures (not text) for definition of compartments [Annex I]. Wine storage can be solved in various ways.
4. Stakeholder reactions on categories & compensation factor [Annex IV]:

   Industry proposal with 4 categories. Doubt about separate wine storage category. NGOs doubt necessity for glass door compensation. Study team clarifies reason for built-in compensation.

Ch. 4 changes: Standards [task 1.2]

1. Do NOT include horizontal issues like ‘smart appliances’ here
2. Humidity control in wine storage not in IEC standard (should be added)
3. Temperature rise test NOT suitable for ‘smart’ usage (food safety issues)
4. Even with 3 test points the new standard saves testing time&costs
5. Circumvention clause essential (ref. to VW)
6. F=0.5 (calculated average at 24°C, from 16 & 32 °C tests) acceptable

Ch. 6 changes: Market Analysis [task 2]

1. China and Turkey are the largest importers **into the EU**. [to add]

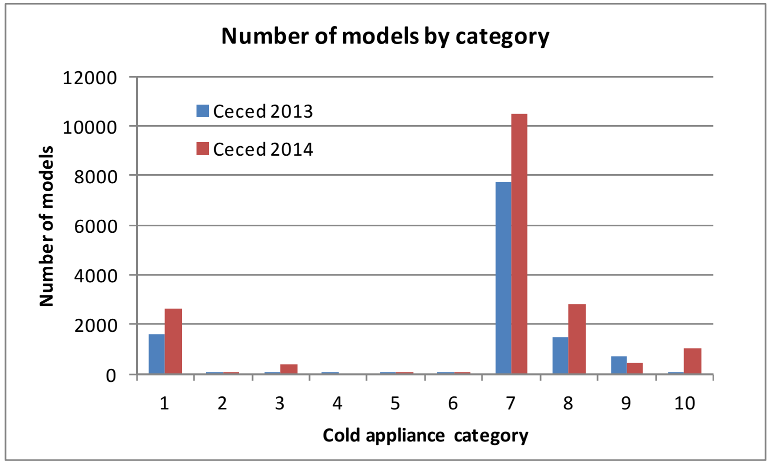
Ch. 7 changes: User analysis [task 3]

1. Storing the food at the correct temperature, BOX 1 added [7.1.4]
2. EoL, durability [7.3.1] : Added more references/source for the limited benefits of refrigerator life extension:
   - Ardente/Mathieux
   - Ricardo-AEA for DG ENV
   - ISO-TR 14062 (2002)
   - Dewulf & Duflou
   - WEEE Directive 2012/19/EU (to prevent re-use)

Chapter 8 [Task 4.1]

Statistical Analysis

Database



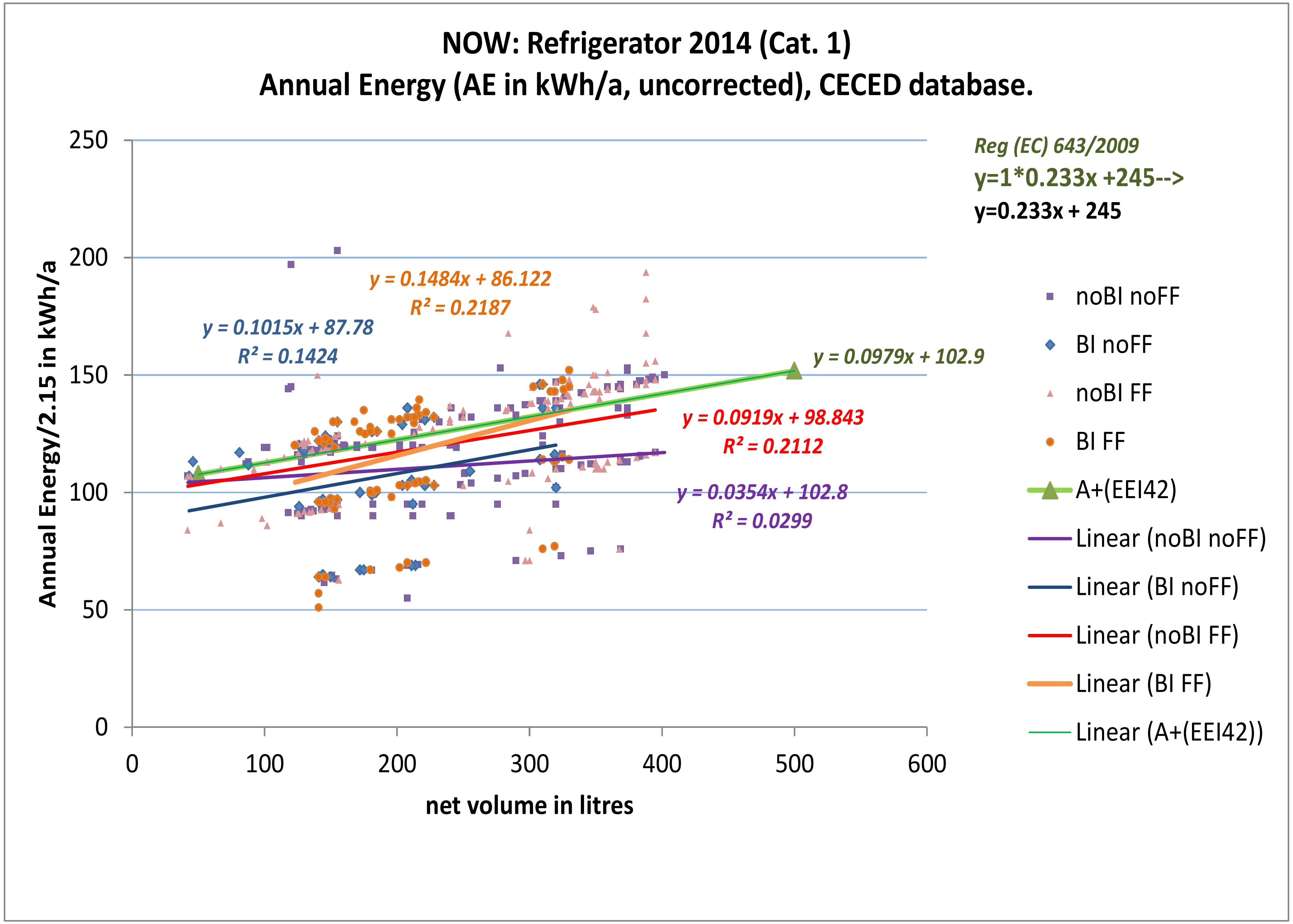
- CECED 2014 database: n= 18 000 models
- Energy label→ bias→ limited use

  still useful as check.

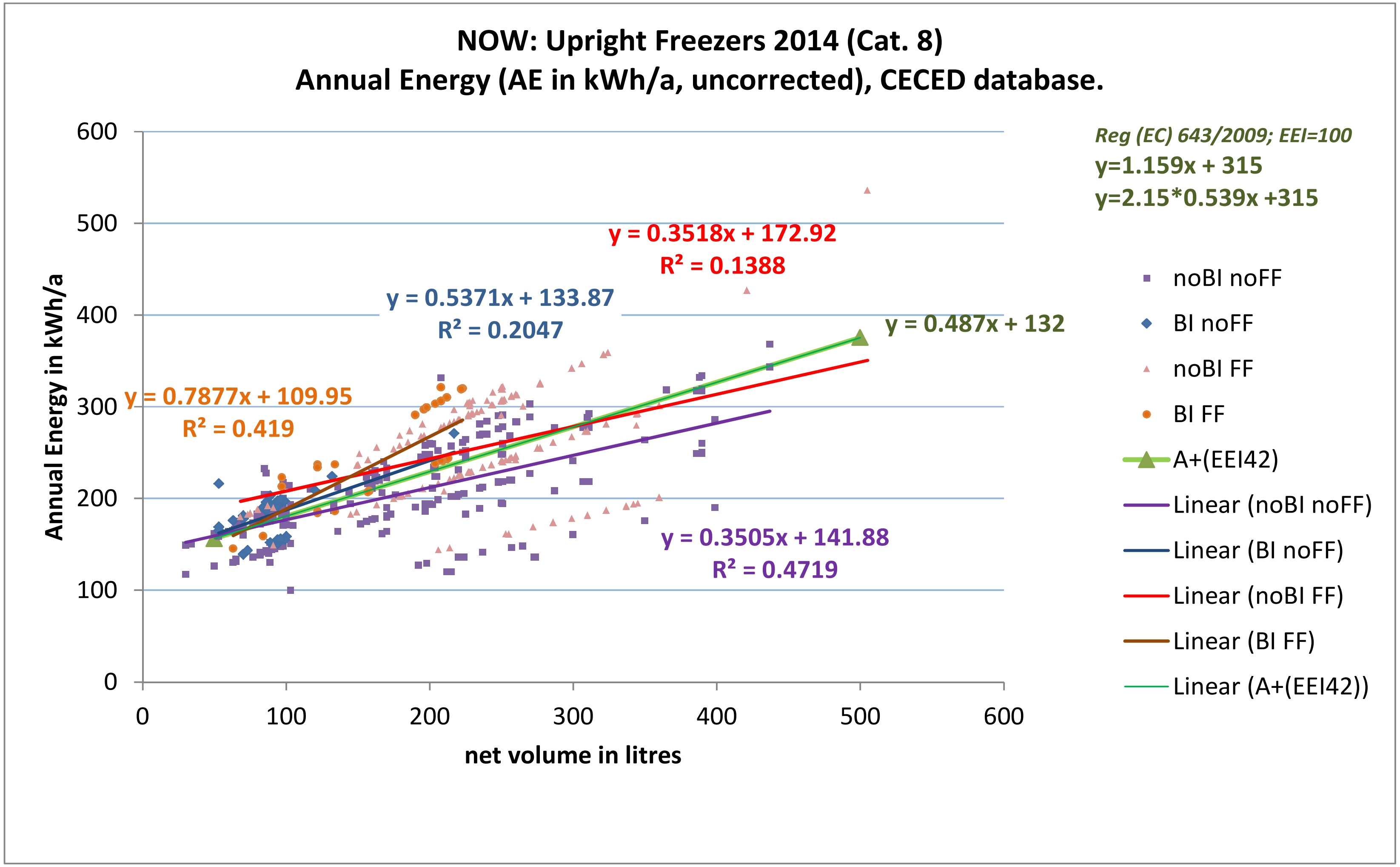
- Step 1: Clean up of errors in classification
- Step 2: Assess averages and totals per (sub) category, energy values without correction, net volumes
- Step 3: Linear regression formulas in XY diagram for kWh/a vs. volume.
- Step 4: Correction for the new standard (at F=0.5): +9% for refrigerator, +6% for fridge-freezer (+10% type I, +3% type II), -5.7% for freezer
- Step 5: Table and graphs, comparison with current A+.

  BI=Built-In, FF=Frost Free

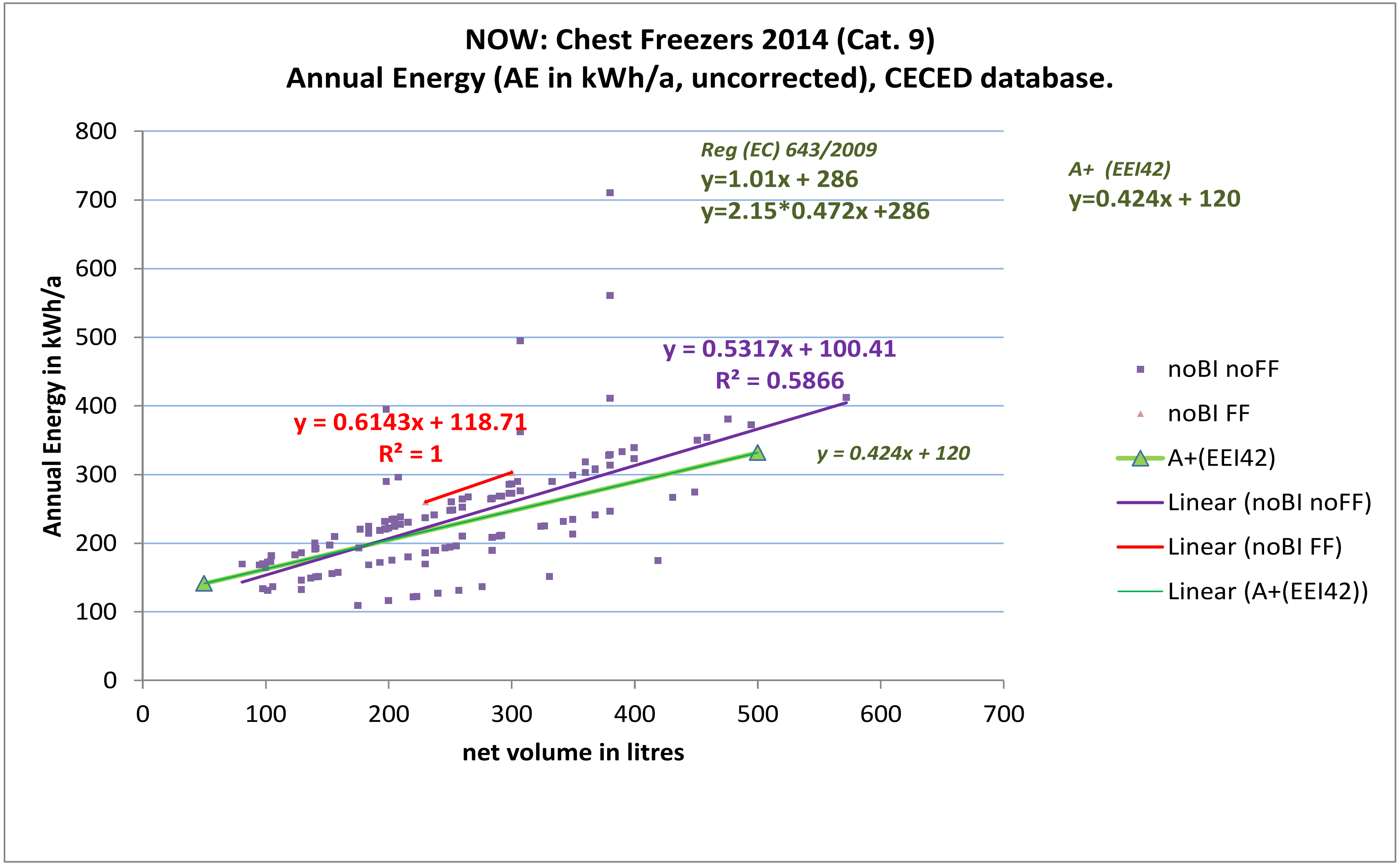
Refrigerator (Cat. 1)



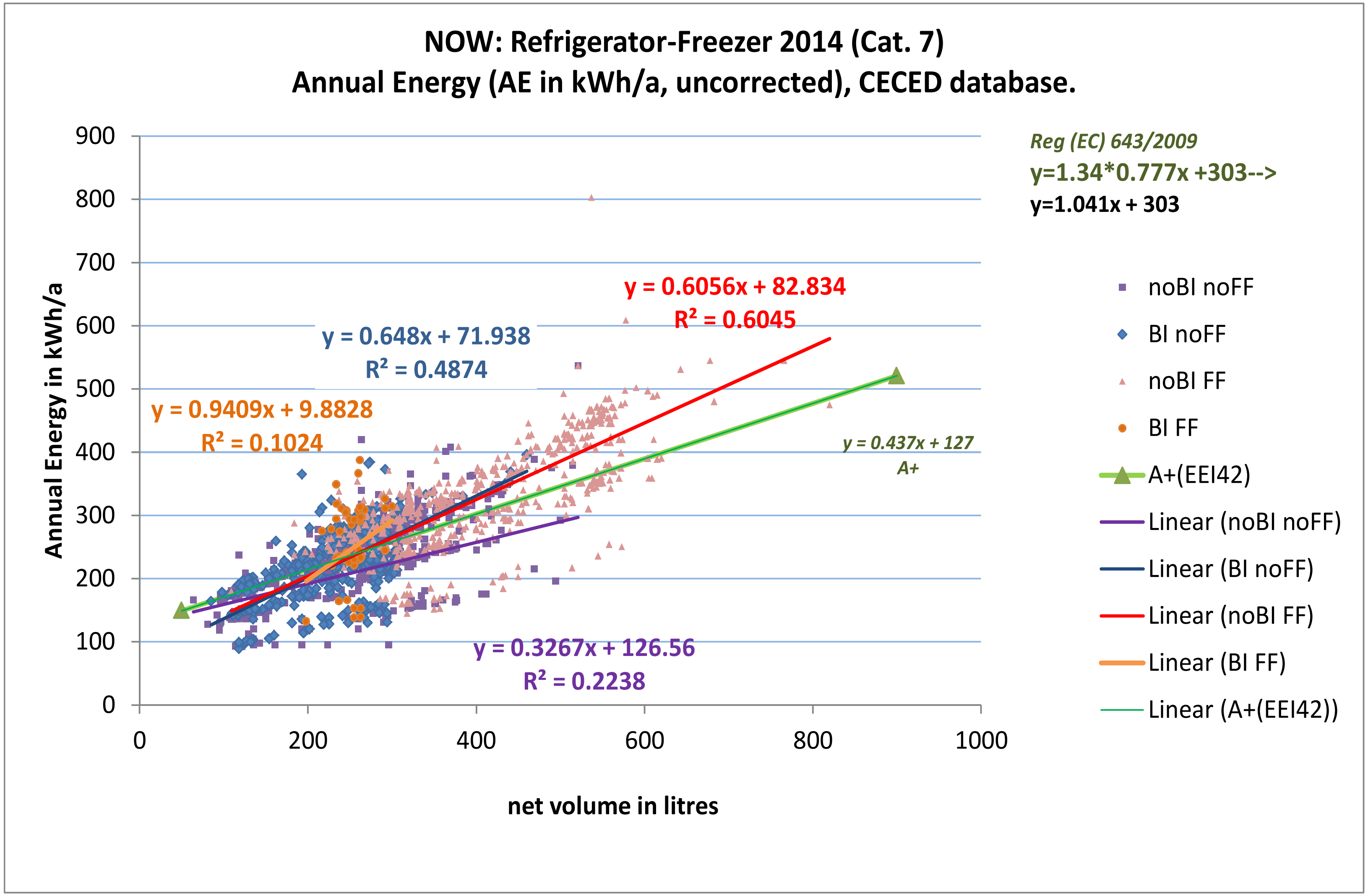
Upright freezer (cat. 8)



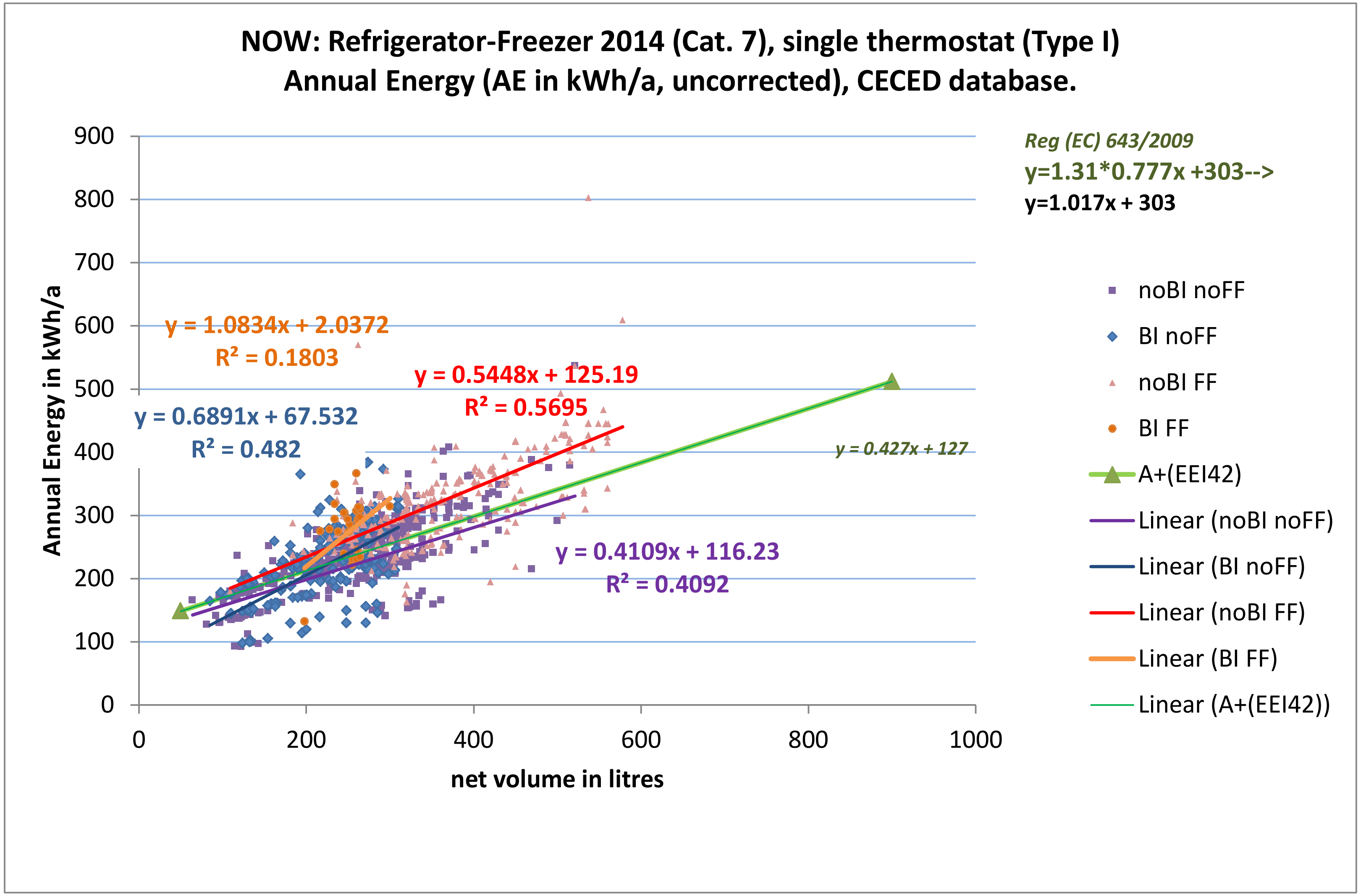
Chest freezer (Cat. 9)



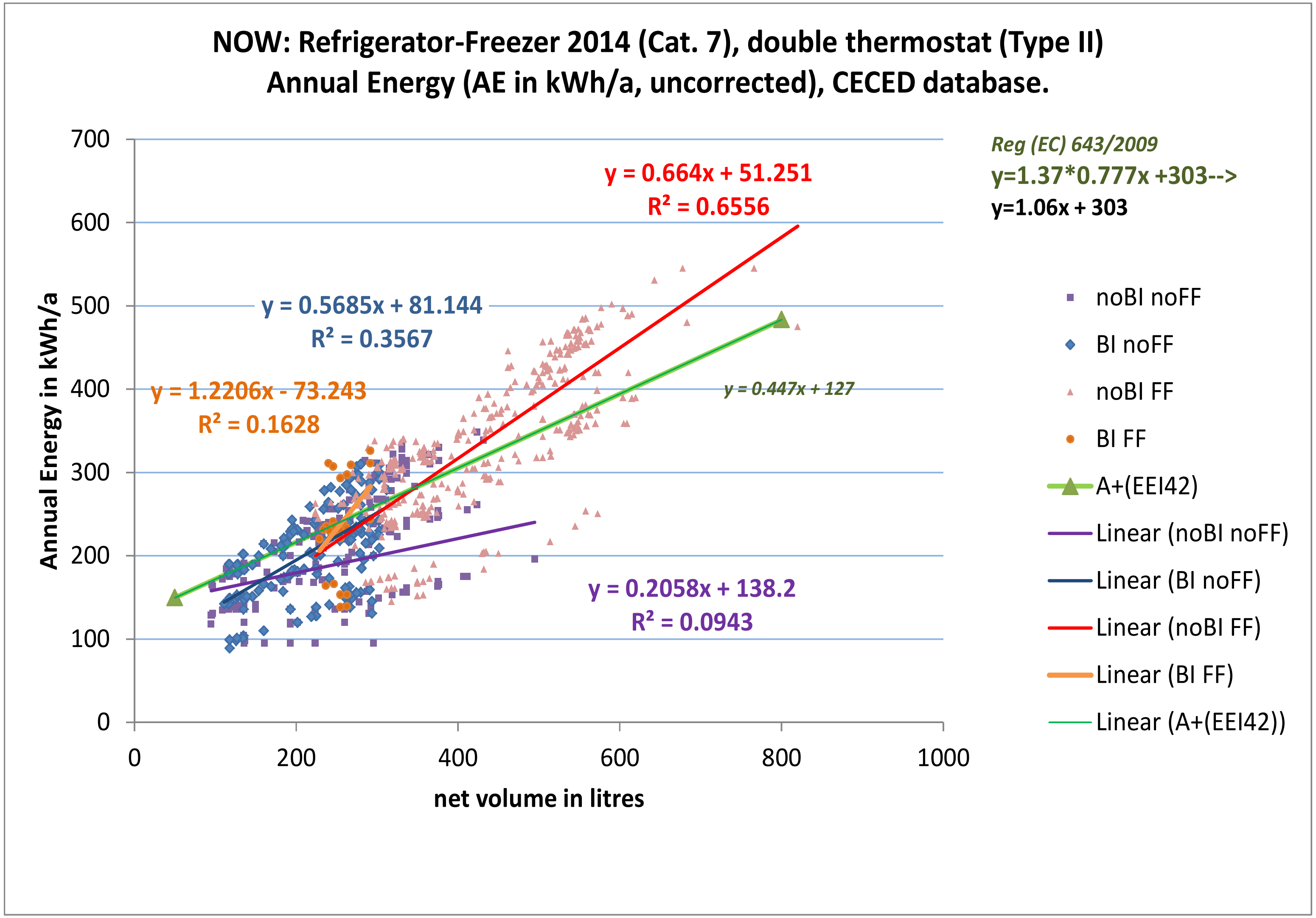
Fridge-freezer, all [cat. 7]



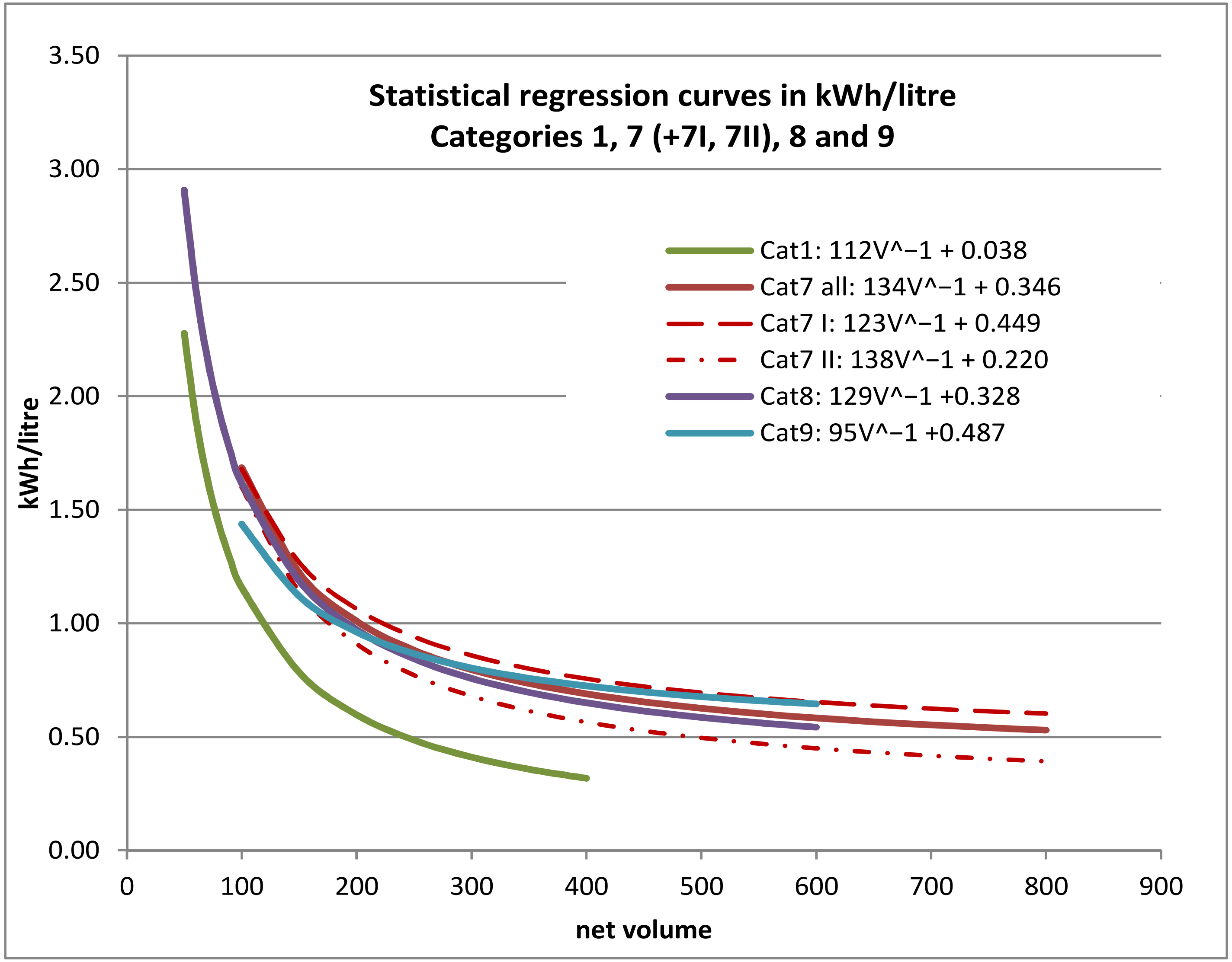
Fridge-freezer, single thermostat [cat. 7]



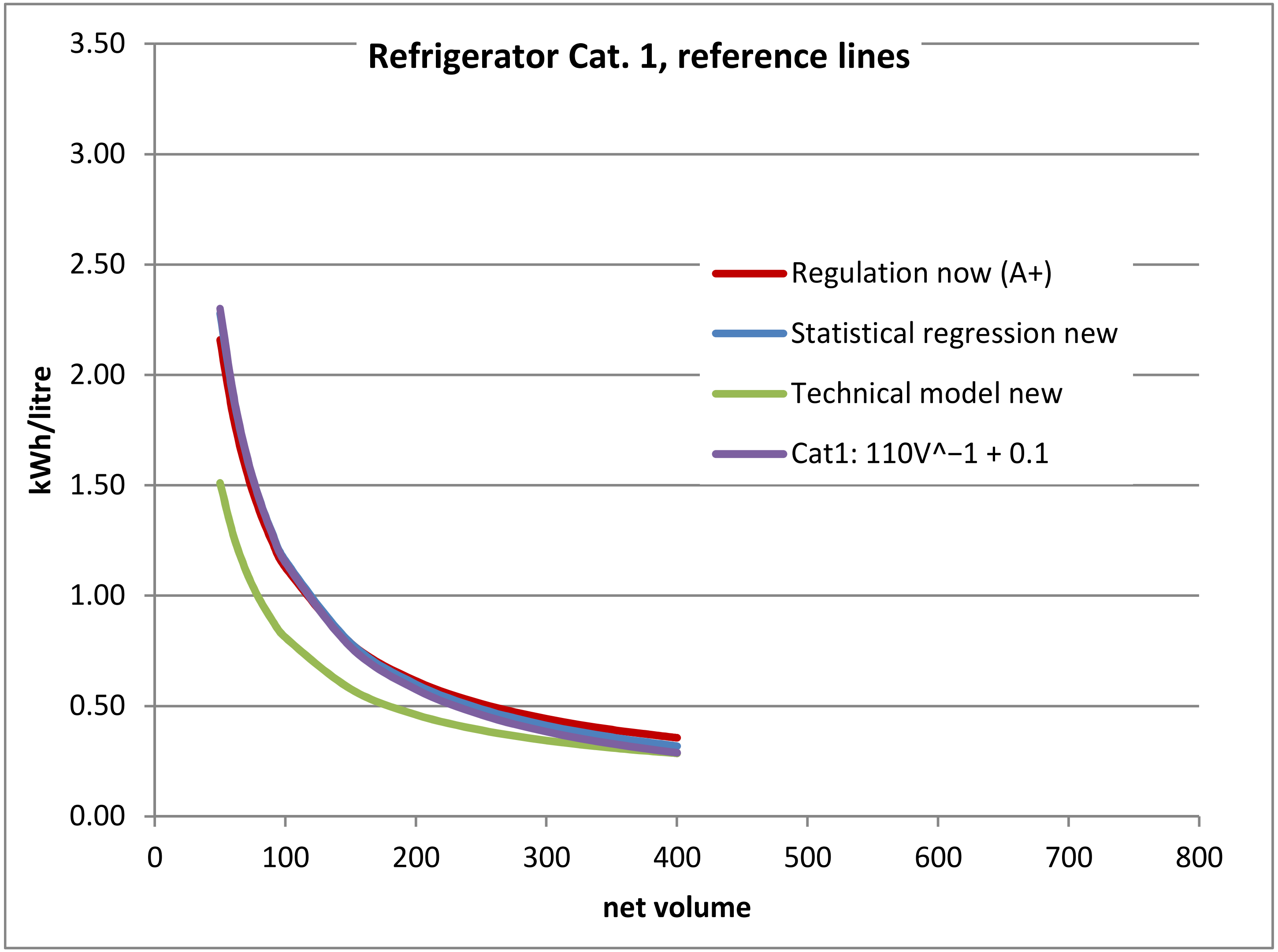
Fridge-freezer, double thermostat [cat. 7]



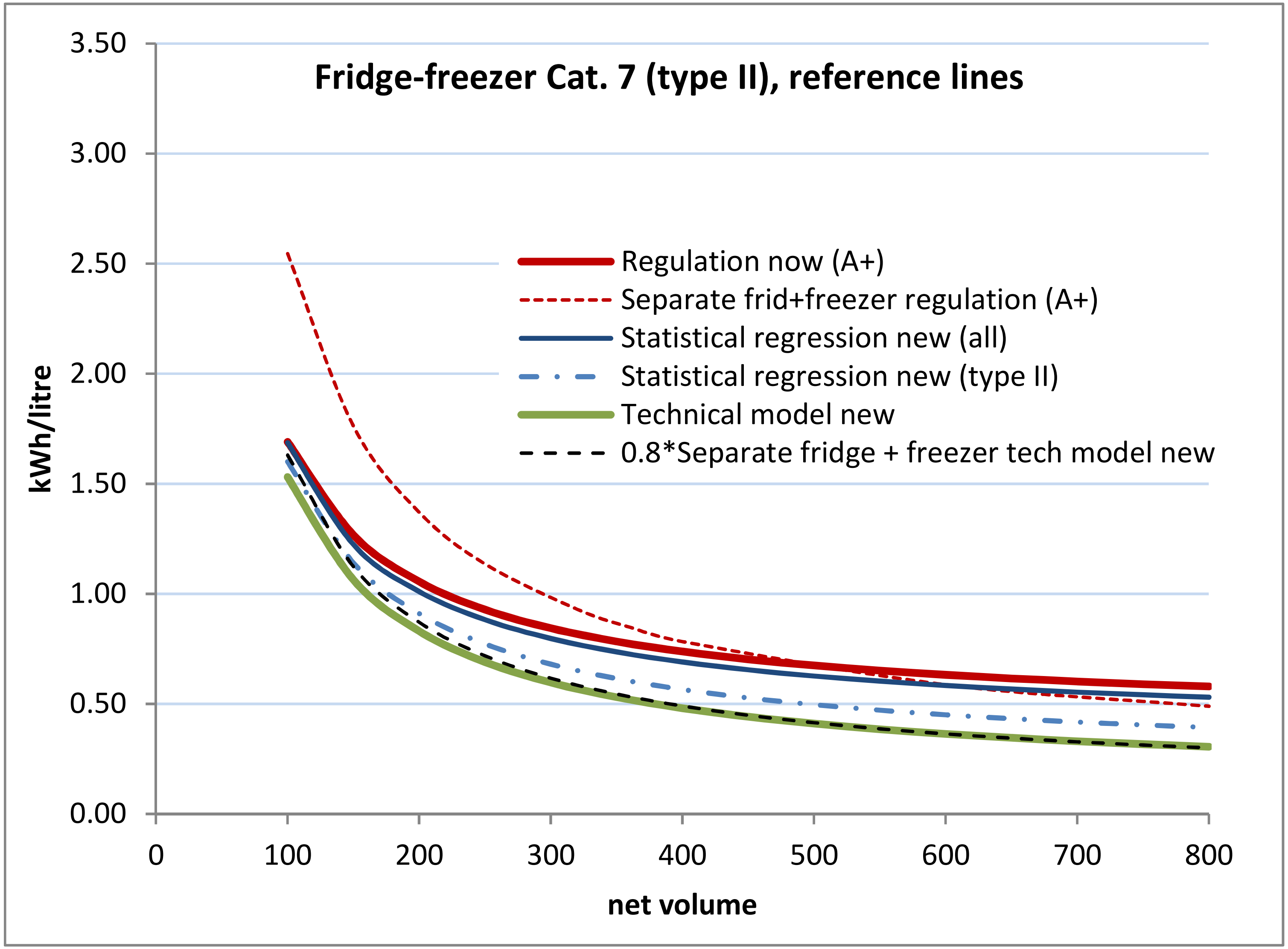
Regression curves NoBI, NoFF in kWh/ltr



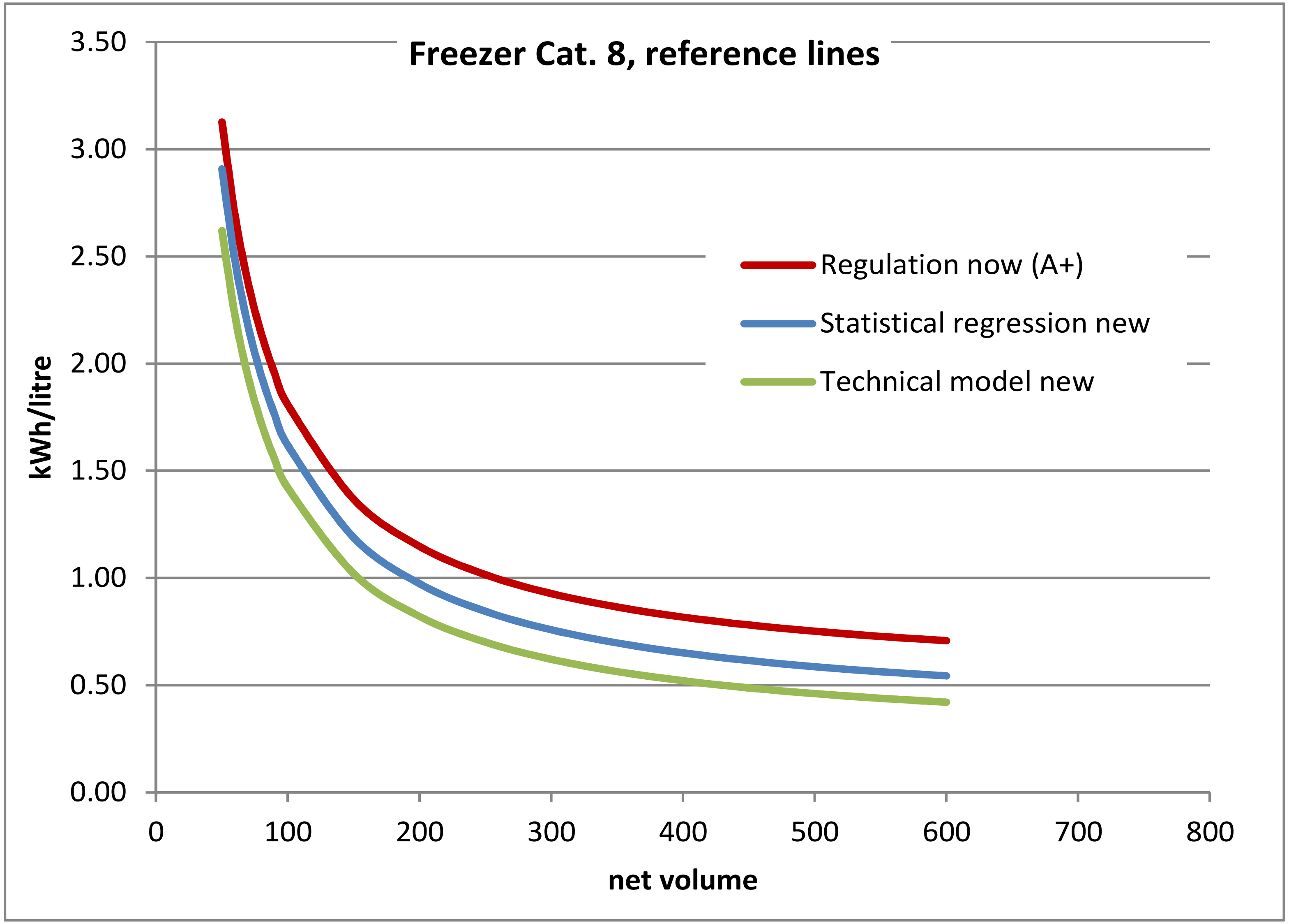
Regression curves refrigerator (cat. 1) in kWh/ltr



Regression curves fridge-freezer (cat. 7) in kWh/ltr



Regression upright freezer (cat. 8) in kWh/ltr



Compensation factors

- FF: 20% per litre freezer volume
- BI: 10% per litre freezer volume; much less for refrigerators
- Wine storage: Little correlation with label

Comparison 2005 (prep.study 2007) -2014

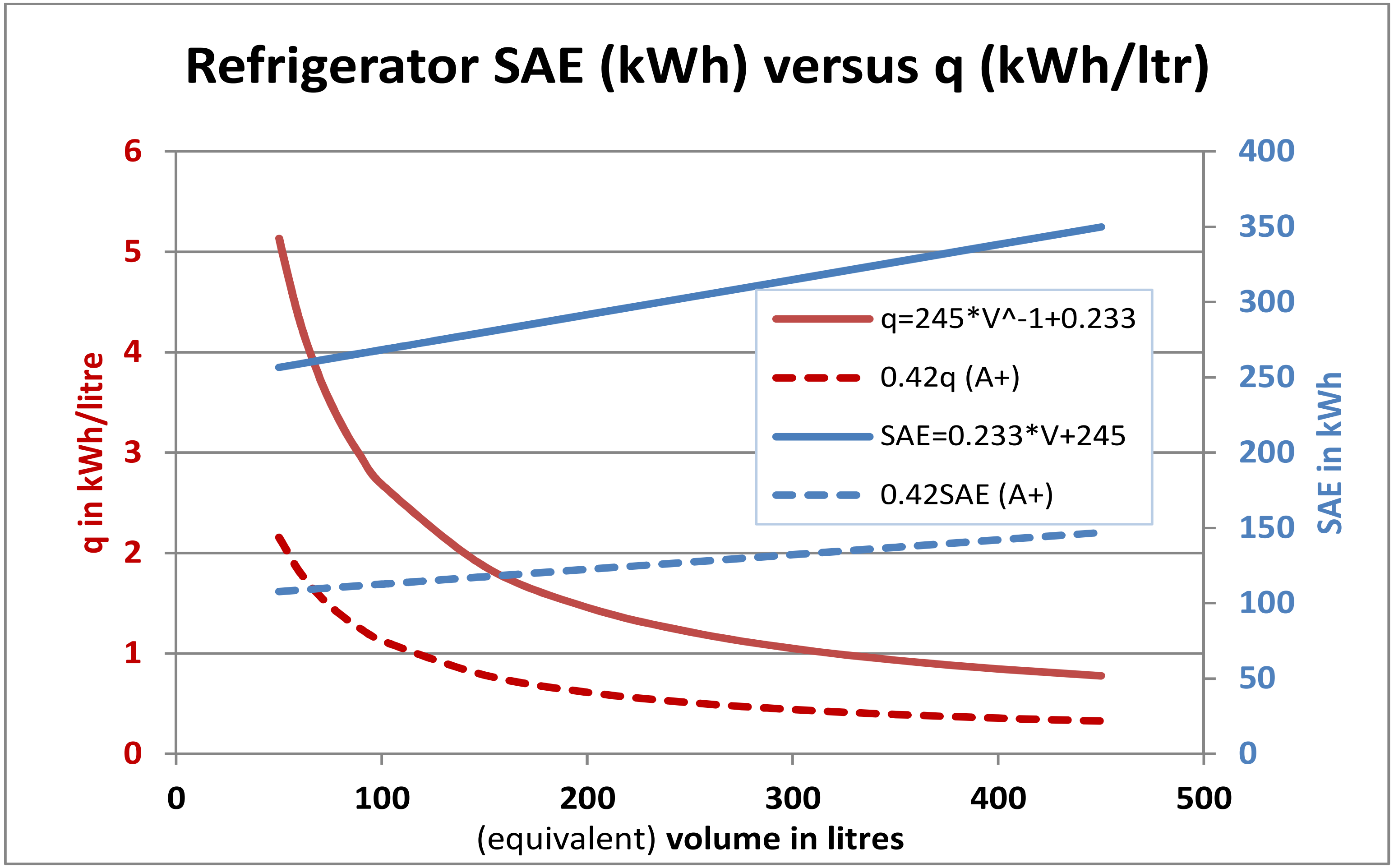
	Net volume (ltr.)		Energy (kWh/a)		Energy (kWh/a)/ltr		EEI (%)		Noise (dBa)	
Category	*2005*	*2014*	*2005*	*2014*	*2005*	*2014*	*2005*	*2014*	*2005*	*2014*
1	223	247	164	119	0.73	0.48	54	36	38	38
7	277	310	324	258	1.17	0.83	54	37	40	39
8	177	203	275	232	1.55	1.14	56	37	40	40
9	254	261	300	236	1.18	0.90	64	39	42	42

Sales weighted average: 11% larger (range 2.7-14.6%), 20% less energy/year, 30% lower energy per litre, 30% lower EEI in 9 years

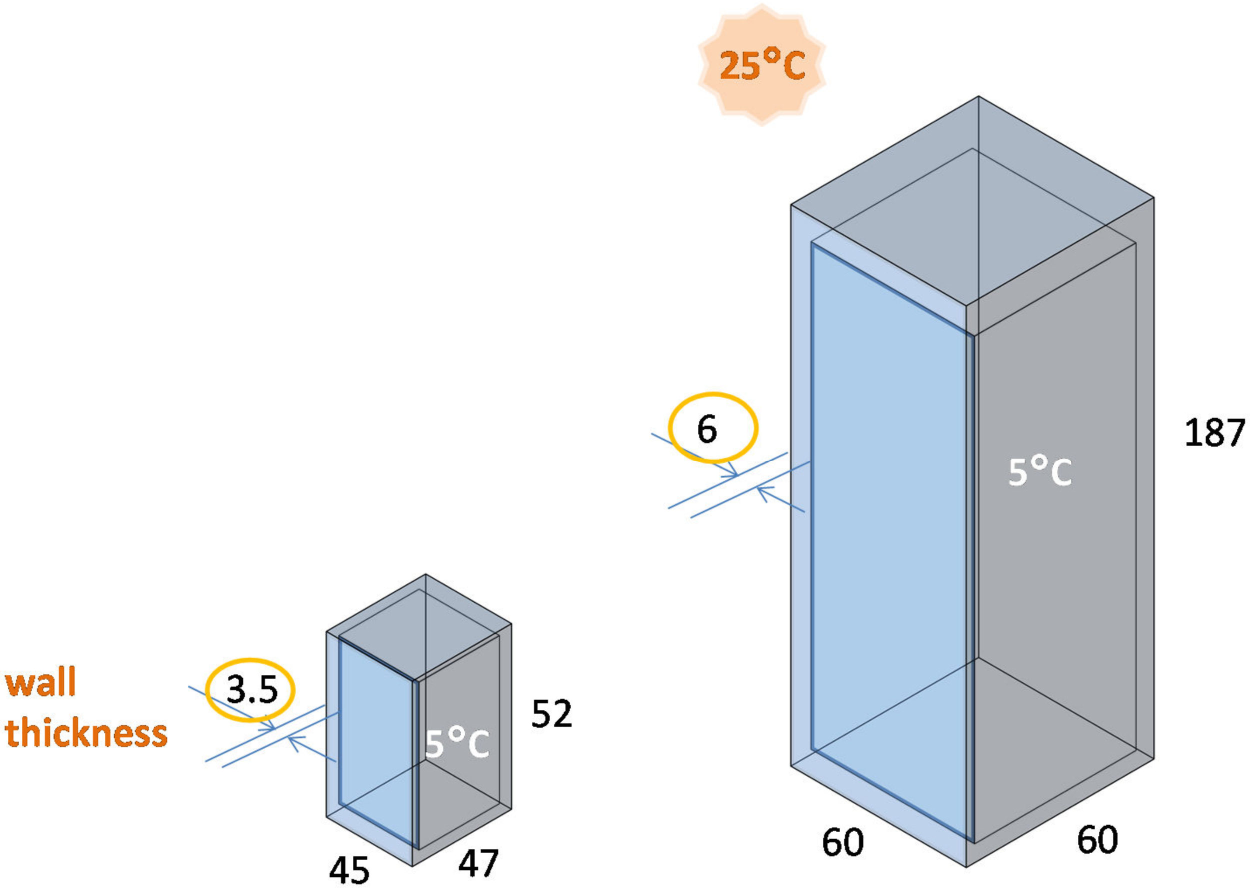
Chapter 9 [Task 4.1]

Technical Analysis & Metrics

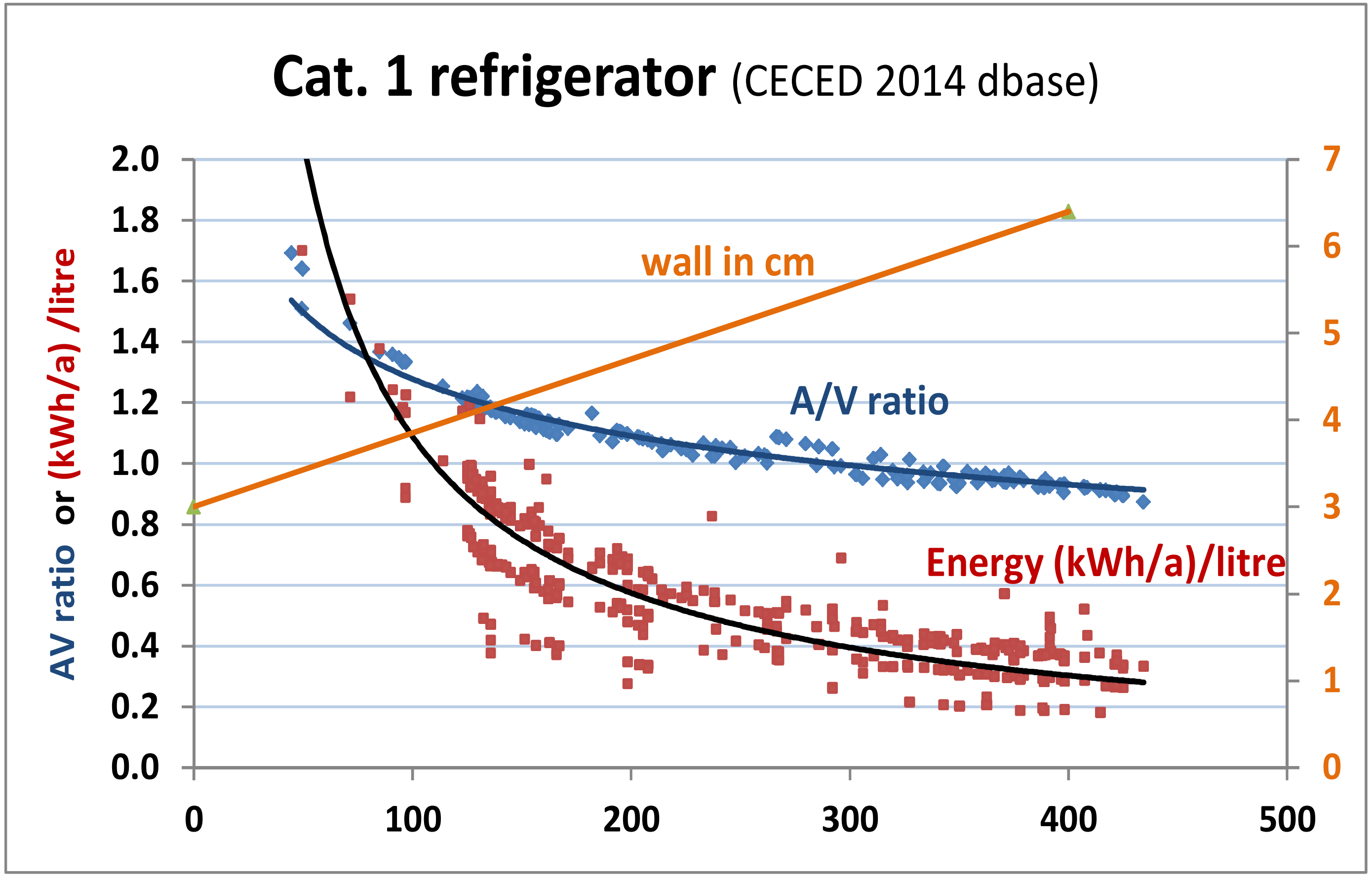
kWh versus kWh/ltr (per year)



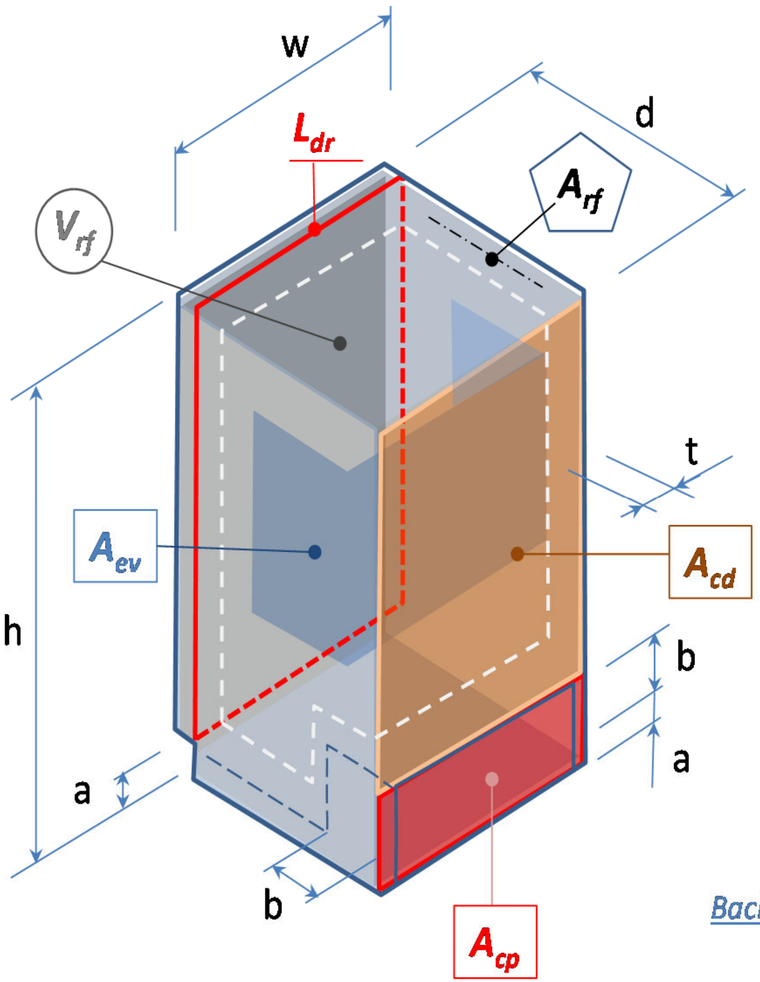
Envelope Area vs. Volume: AV ratio



Plausible curves



Domensions



Refrigerator geometry parameters

V_{rf}	refrigerated volume (m^3)
A_{rf}	refrigerator envelope surface (m^2)
A_{cd}	condensor area (m^2)
A_{cp}	compressor area (m^2)
A_{ev}	evaporator area (m^2)
L_{dr}	door perimeter length (m)
w	width (m)
d	depth (m)
h	height (m)
a	air passage height below unit (m)
b	height/depth compressor area (m)
t	average wall thickness (m)

Back view

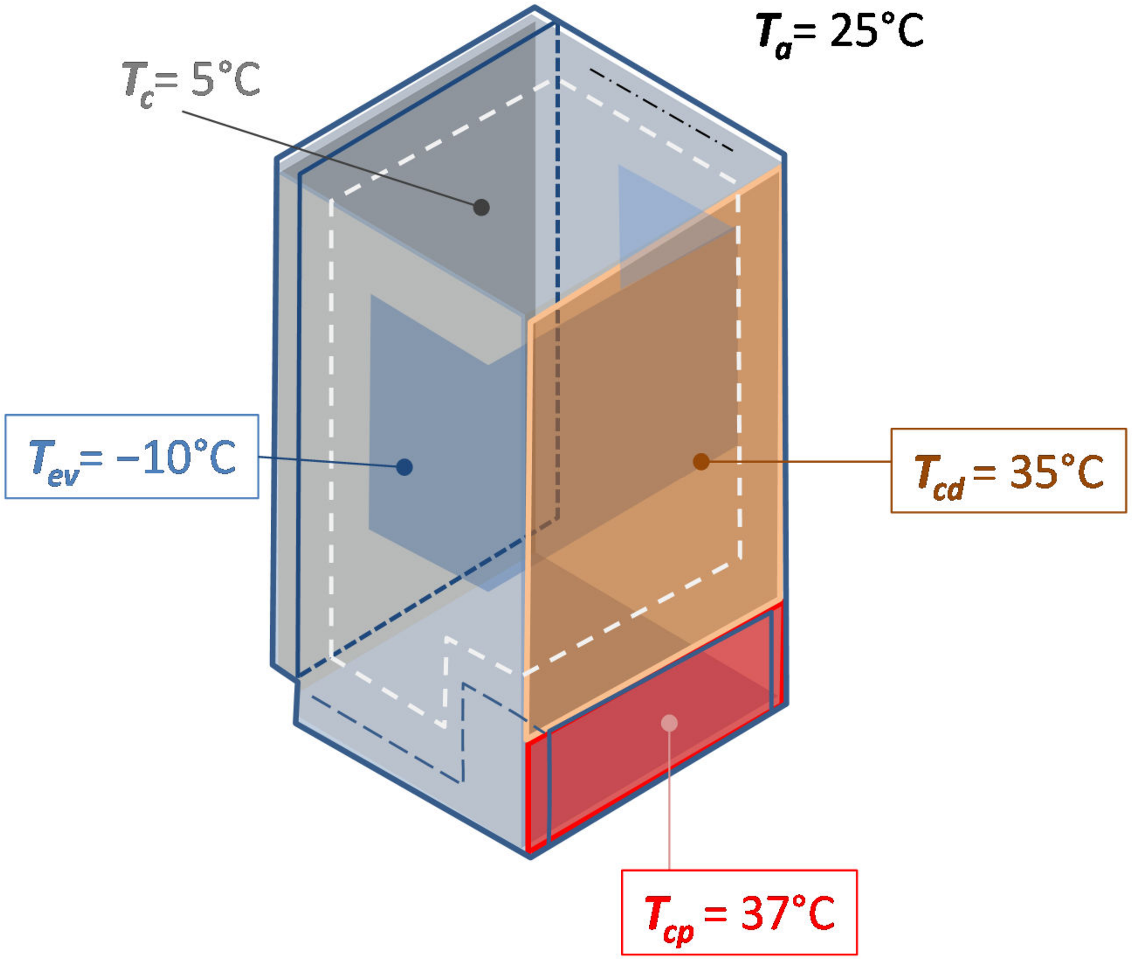
Equations

- $V_{rf} = (w-2t)\cdot(d-2t)\cdot(h-a-2t) - b^2\cdot w$
- $A_{rf} = 2\cdot(w-t)\cdot(d-t) + 2\cdot[(h-t-a)\cdot(d-t)-(b+0.5t)^2] + 2\cdot(w-t)\cdot(h-t-a)$
- $A_{cd} = w\cdot(h-a-b)$
- $A_{cp} = w\cdot(a+b)$
- $L_{dr} = 2\cdot(w+(h-a))$

For dimensions a and b fixed values of a=0.05 m and b=0.2 m can be assumed.

CECED corrections to be applied (small, relates to compressor space)

Basic temperature map



U-values

Table 18. U-values (source: Ecodesign Windows study 2015)

Glass door U-values glass+frame (70/30% of area)	**W/(m².K)**	
double glazing simple	2.8	
double glazing E-coating, argon fill	**1.7**	reference (economical, normal, etc.)
double glazing E-coating, krypton fill	**1.3**	for premium models
triple glazing E-coating, argon fill	1.1	very heavy door (hinge needs mechanical help)
triple glazing as above but middle 'glass' is film	1	estimate (door is lighter)
triple glazing E-coating, krypton fill	0.8	very heavy door (BAT)
vacuum glazing (double glass with studs)	0.8	Experimental; door would be lighter (BNAT)
quadruple glazing, E-coating, krypton fill	0.6	impossibly heavy for fridge door (BAT for fixed windows)
Refrigerator insulation	**W/mK**	Watts per meter thickness and K
PUR + cyclopentane	0.020	for average size, i.e. 270 litre, 6cm is normal
VIP	0.005	
Combined 40% VIP (2 cm), 60% PUR (3 cm)	0.015	

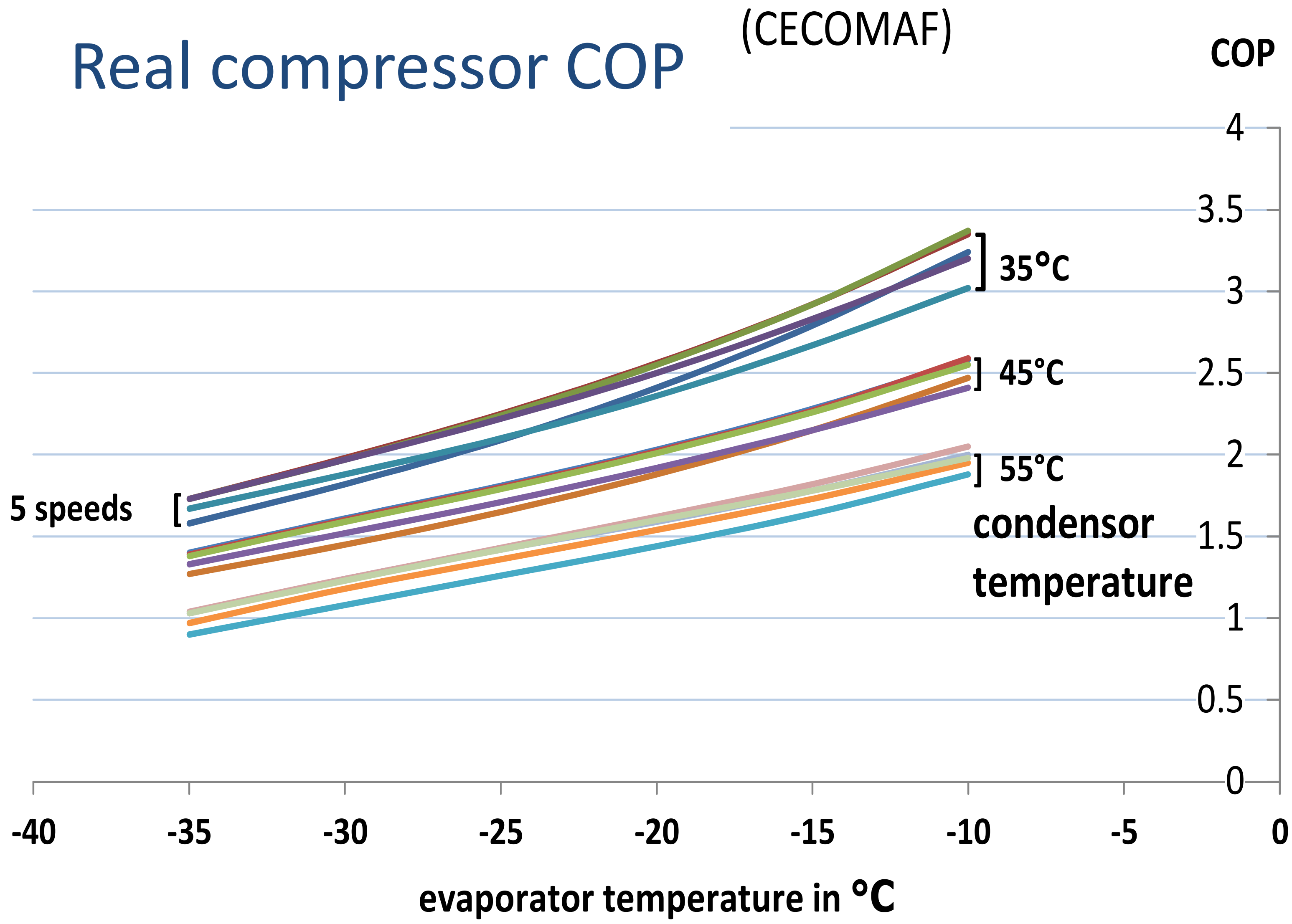
COP basics

$$COP_{Carnot} = \frac{T_{ev}+273.15}{T_{cd}-T_{ev}}$$

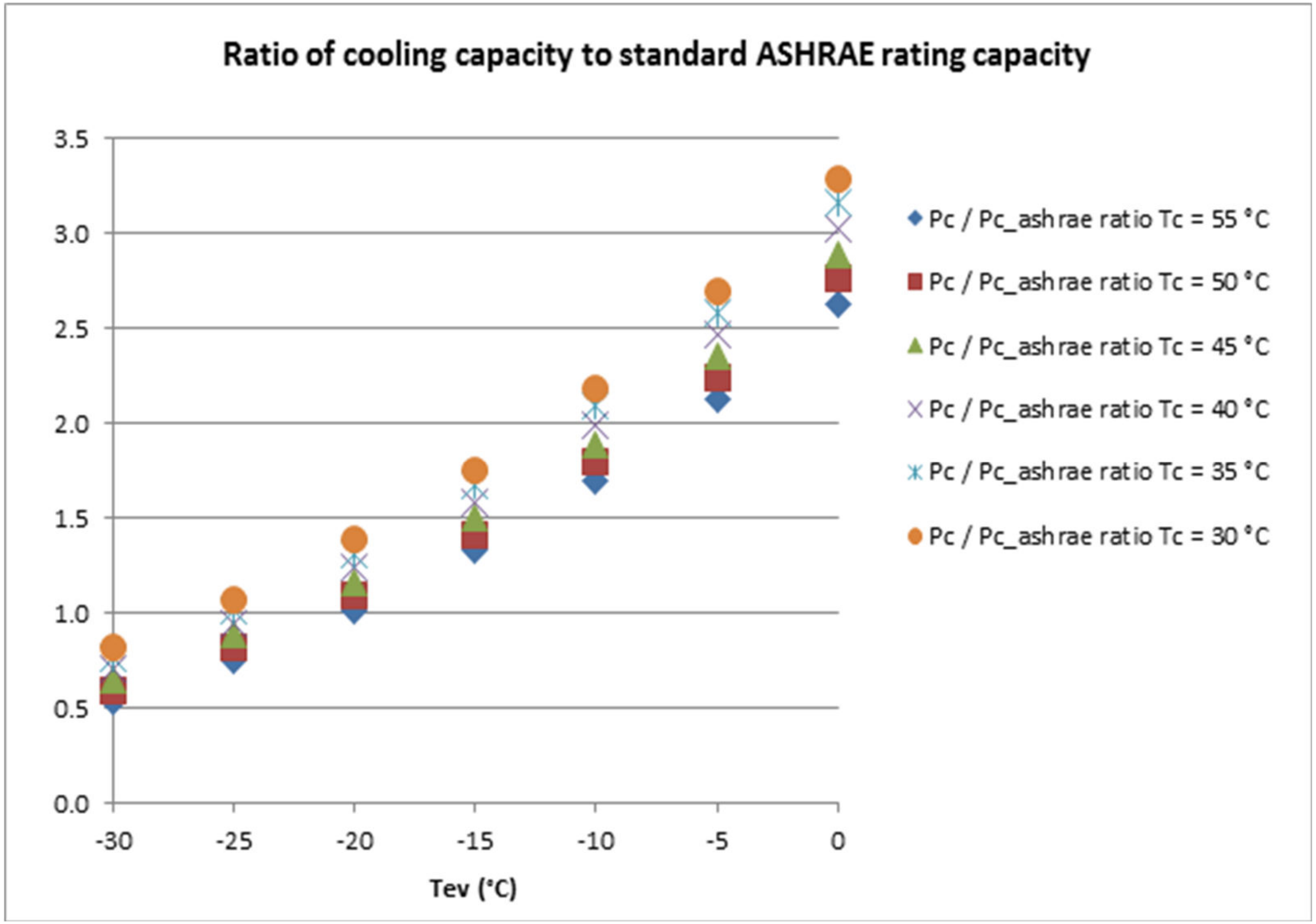
- $COP_{real} = \eta_{Carnot} \cdot COP_{Carnot}$
- $\Delta T_{ev} = T_c - T_{ev}$ [15, 8, 10 K for fridges, combis , freezers resp.]
- $\Delta T_{cd} = T_{cd} - T_a$ [10, 10, 12 K for fridges, combis , freezers resp.]

- *Control features: variable speed, no. of thermostats, etc.*

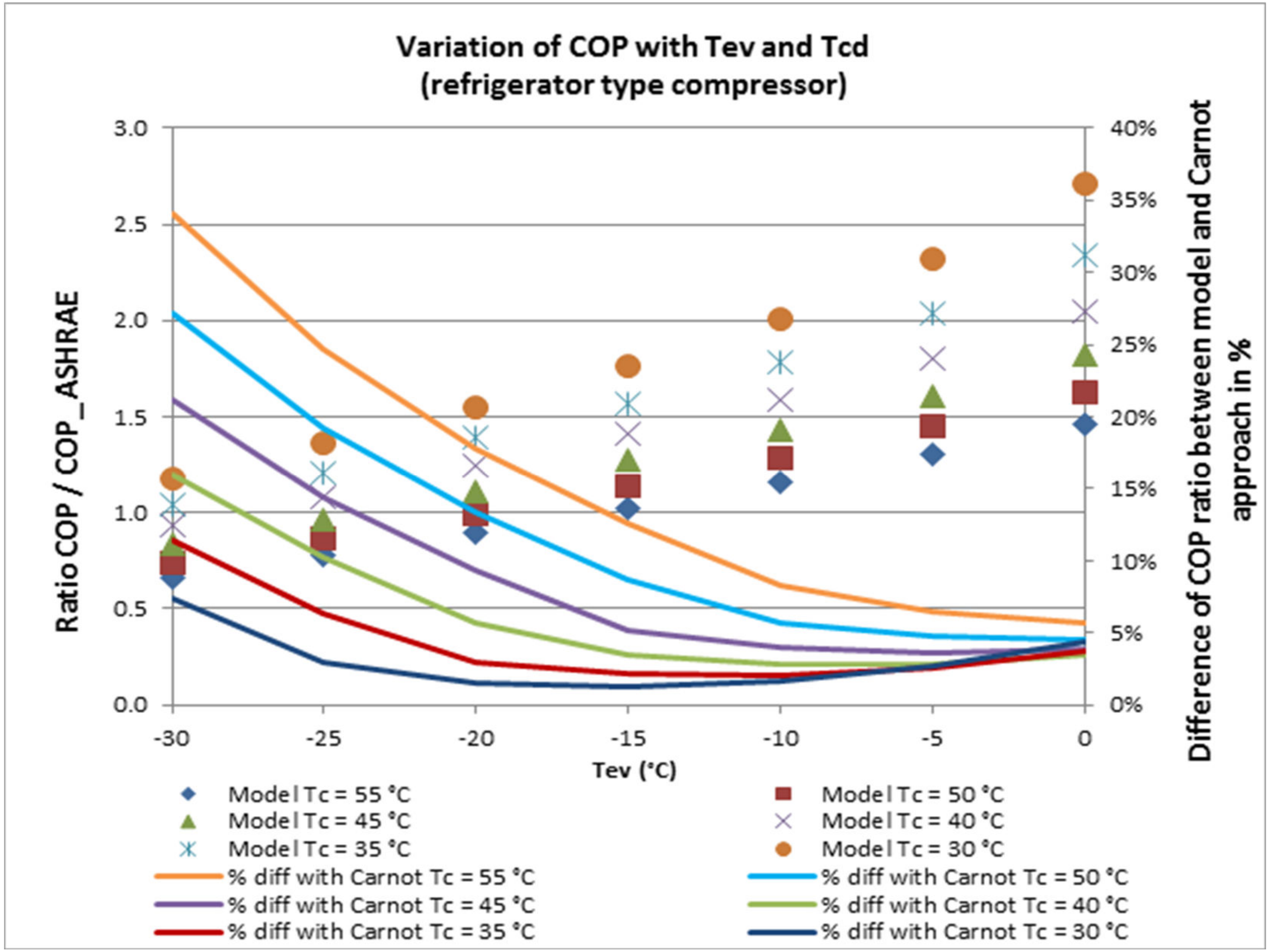
Real compressor COP



Cooling capacity: ASHRAE-conditions versus real *Tev* and *Tcd*



COP-variation with *Tev* and *Tcd*



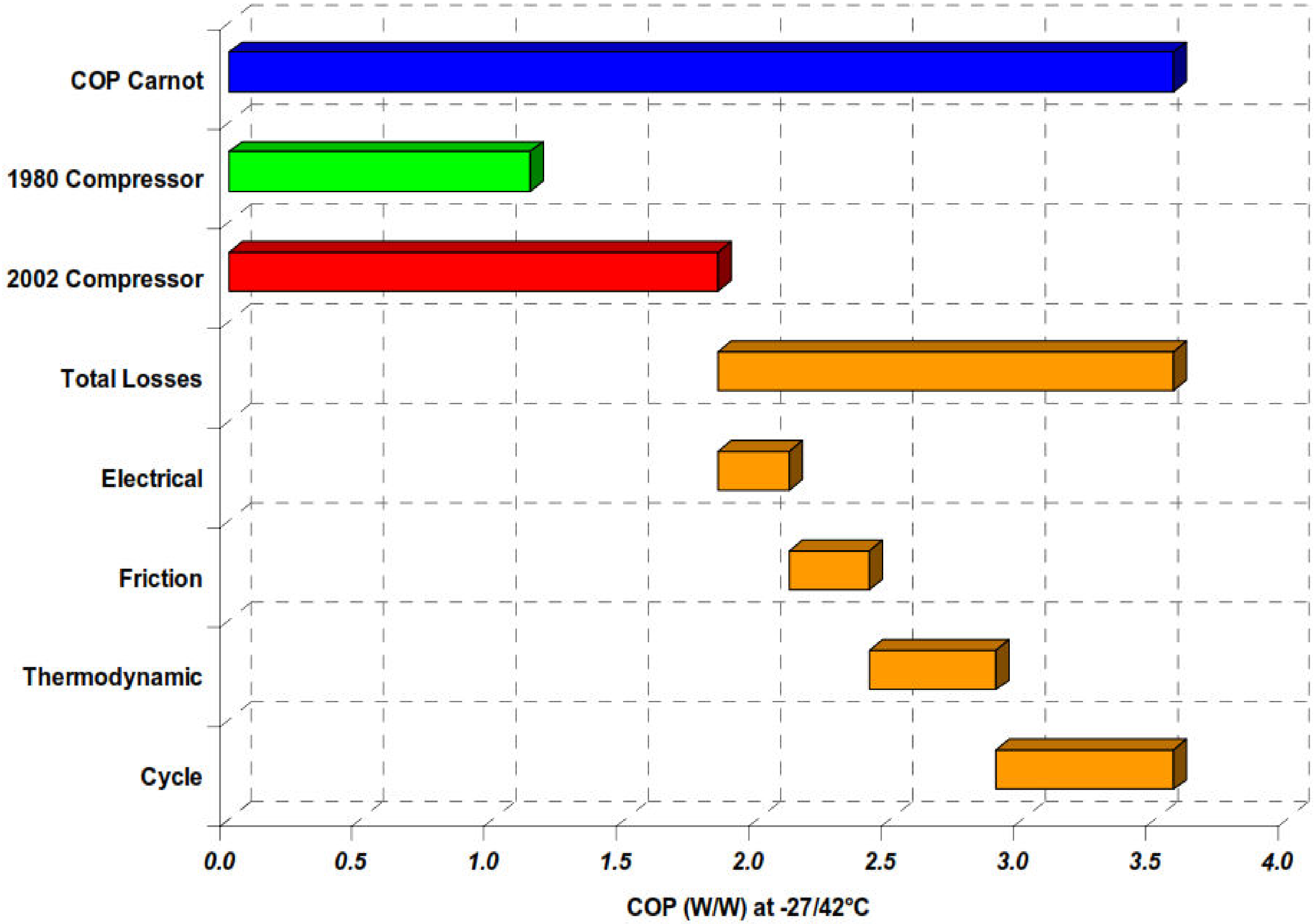
Cycling losses

$$COP / COP_{ss} = 1 - Cd \cdot (1 - Load / Pc)$$

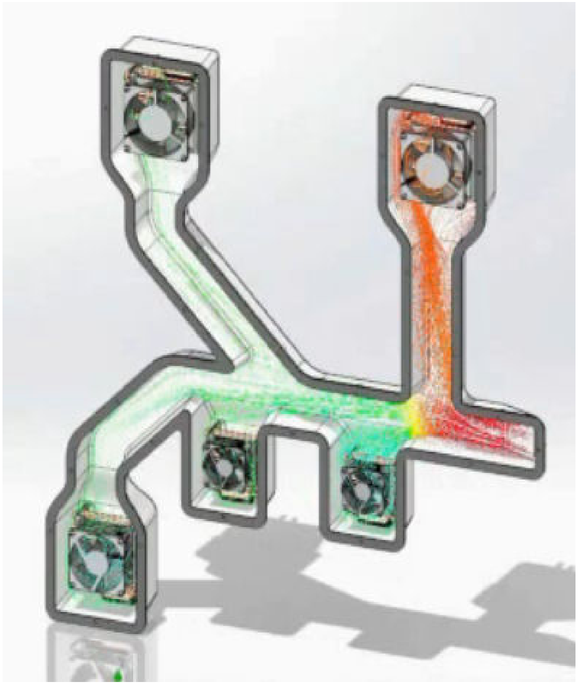
with

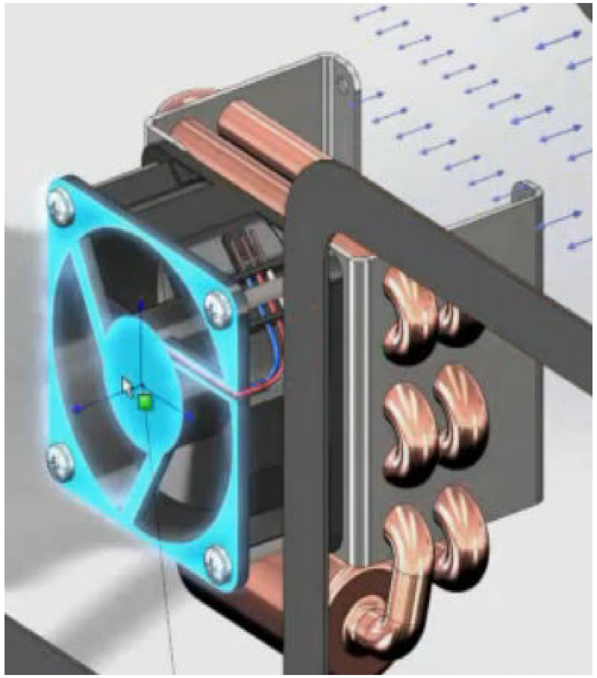
- *COP* is average COP over an on/off cycle
- COP_{ss} is COP in steady state operating conditions (without cyclic operation)
- *Cd* is cycling losses degradation coefficient [0.125 in study]
- *Load* is thermal load to be extracted from the fridge by the compressor (in W)
- *Pc* is cooling capacity at given *Tev* and *Tcd* (in W)

Hermetic compressor efficiency/COP



Multi-duct (illustration)





Reference line metrics development

- Preliminary proposal study team in report 14.11.’15, based on technical approach
- Comments CECED 7.12.2015 [agrees with technical approach but with adjustments]
- Presentation of consensus values & discussion
- Mainly combi-factor to be further developed, but note that we do not have to be better than today (where there is also a fixed M and N value for <u>every</u> combination in cat. 7)

Single equation (1st proposal)

A single equation for the reference specific energy use q_{ref} (the new ref for 'EEI=100')

$$q_{ref} = D \cdot \sum_{c=1}^{n} A_c \cdot B_c \cdot C_c \cdot \left(\frac{N_c}{V} + r_c \cdot M_c\right)$$

in kWh/litre per year,

With

- q_{ref} is reference electricity consumption in kWh/litre volume (V_{net}) annually
- A_c is auto-defrost compensation factor (1.2 for frozen food compartments),
- B_c is built-in compensation factor (1.1 for compartments with $T_c < 0$°C, 1.04 for $T_c \geq 0$°C),
- C_c is combi-factor, consensus on C_c=1 for single compartment → *see next slides for combi*
- D is door heat loss more than 2 doors (1.02/1.035/1.05 for appliances with 3/4/>4 doors),
- n is number of compartments, c is compartment index suffix,
- N_c, M_c are constants specific for a compartment c → *see table next slides*
- V is total net volume of the appliance, V_c is compartment net volume,
- r_c is temperature correction, with $r_c = (T_a - T_c)/20$ where T_a = ambient temperature, T_c= compartment temperature (both in °C)

Combi-factor variations

1.

Preliminary proposal report (with formula previous slide) : $C_c = 0.7 \cdot (r_c \cdot V_c/V)$ which is $C = 0.917$ overall for a combi with 73% fresh food ($r_c = 1$) and 27% frozen food ($r_c = 2.1$) net volume [looks roughly OK there, but correction is too strong e.g. for 50%/50% combi→ C>1]

2.

CECED preliminary proposal 7.12.2015

$$q_{ref} = D \cdot \sum_{c=1}^{n} A_c \cdot B_c \cdot C_c \cdot \left(\frac{N_c}{\boldsymbol{V_c}} + r_c \cdot M_c \right)$$

with $C_c = C_1 \cdot (V_c/V)$, with $C_1 = 0.87$ (preliminary value for fridge/freezer volume 73/27%)

3.

Simpler basic alternative (also inspired by earlier industry proposals)

$$q_{ref} = C \cdot D \cdot \sum_{c=1}^{n} A_c \cdot B_c \left(\frac{N_c}{\boldsymbol{V}} + r_c \cdot M_c \right)$$

With $C = 0.87$ x limited correction factor (range 1±10%?) for models that deviate from 73% fresh food/27% frozen food [to be developed, e.g. 1.07 for 50/50%]

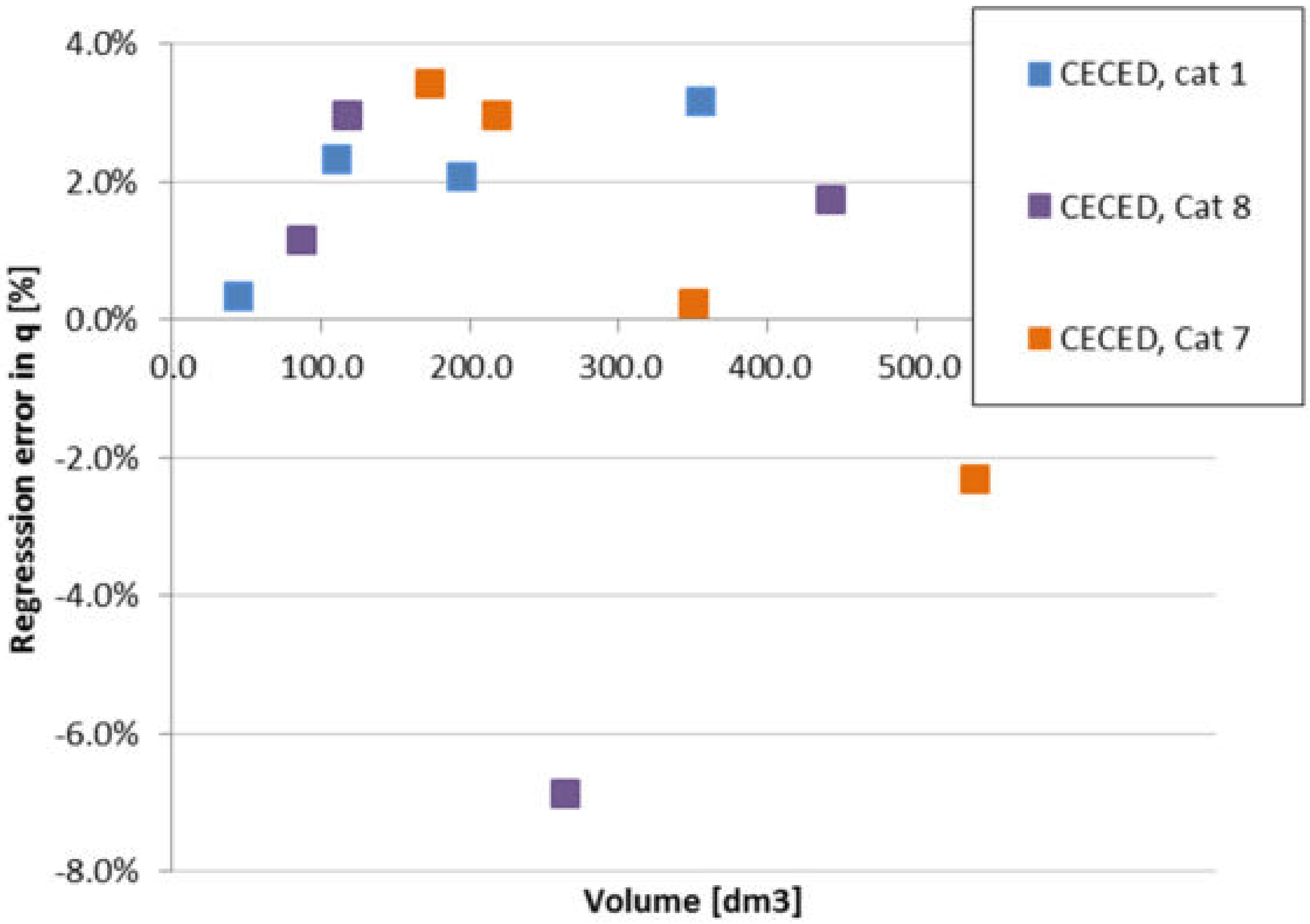
N, M, r_c and temperatures

Compartment	T_{min}	T_{max}	T_c	r_c	B_c	Study N_c	Study M_c	CECED N_c	CECED M_c
Name	°C	°C	°C						
Pantry	+14	+20	+17	0.35	1.04	**75**	**0.12**	**72**	**0.13**
Wine storage [1]	+5	+20	+12	0.60					
Cellar	+8	+14	+12	0.60					
Fresh food	+4	+8	+4	1.00					
Chill	−2	+3	0	1.20					
0-star & ice-making	*n.a.*	0	0	1.20	1.1	**100**	**0.21**	**115**	**0.15**
1-star freezer	*n.a.*	−6	-6	1.50					
2-star freezer	*n.a.*	−12	-12	1.80					
3/4-star freezer	*n.a.*	−18	-18	2.10					

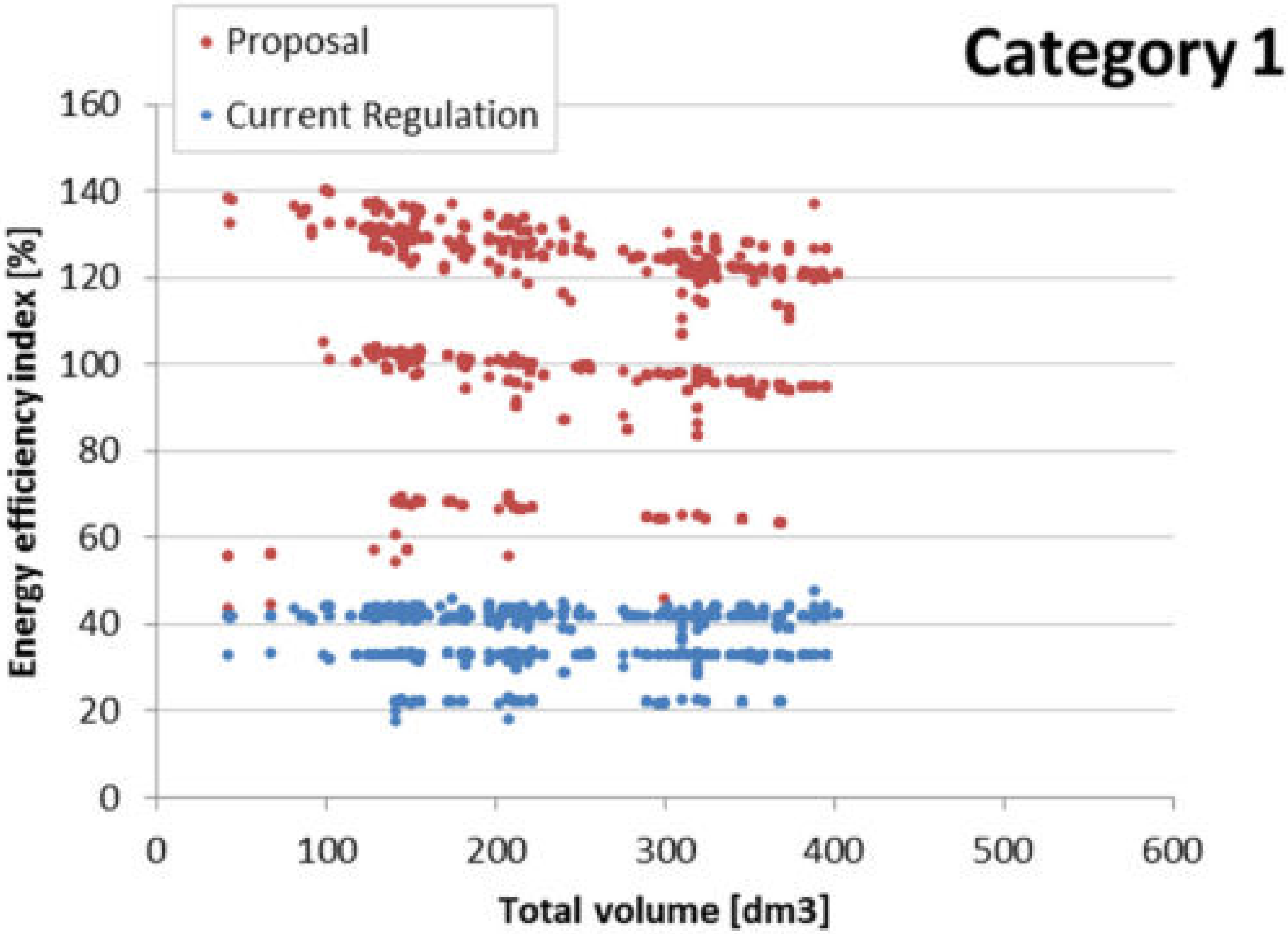
Fridges similar. Freezers: CECED concludes to different volume dependance *Nc* and lower constant *Mc* for freezers with adjusted technical model → valid reasons according to study team and proposes to adopt CECED values

Discussion still on correction of CECED values for new standard → higher for fridge: 77/0.14, lower for freezer 108/0.14, 1st rough estimates.

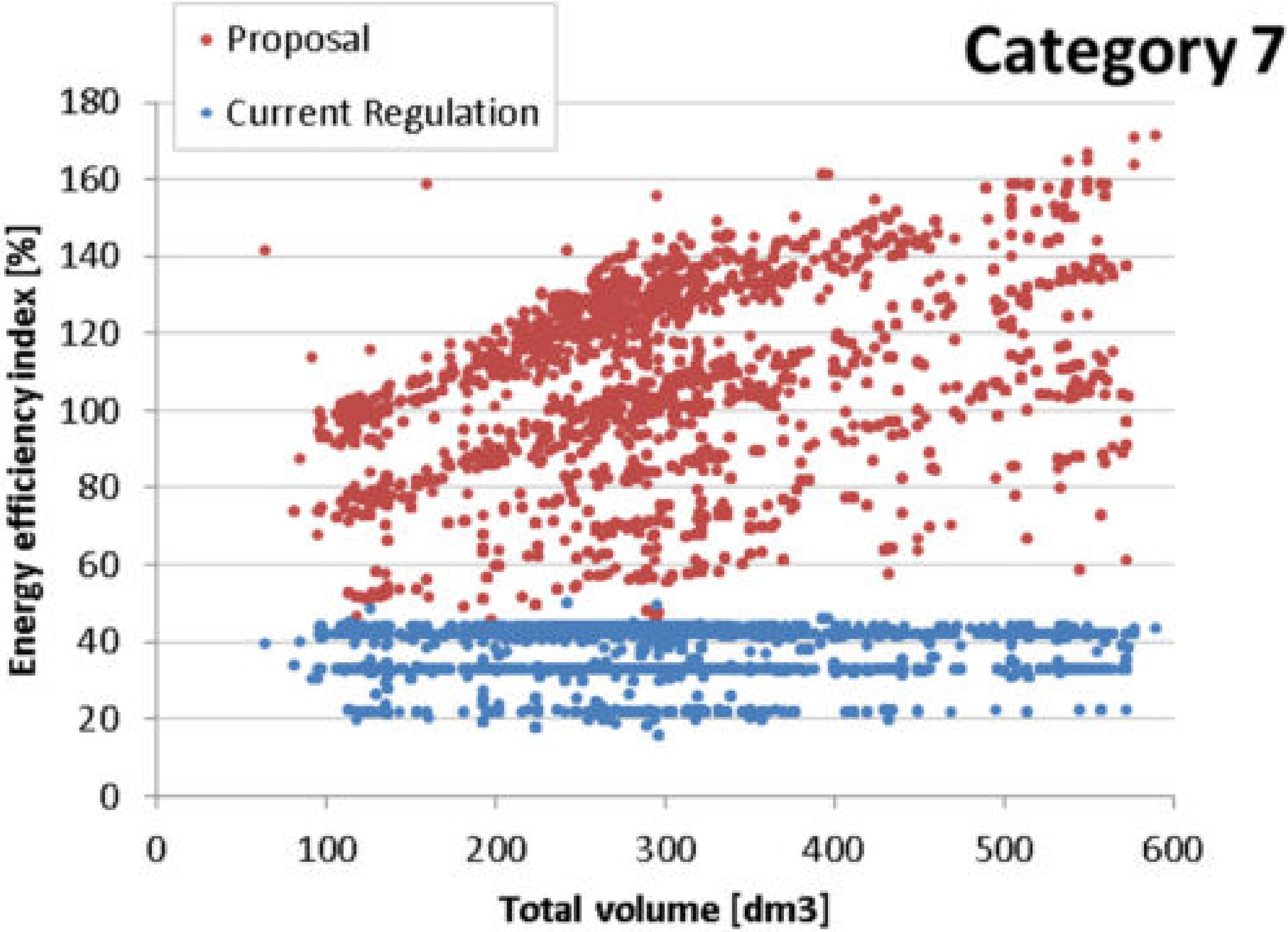
CECED error diagram (model vs. Formula)



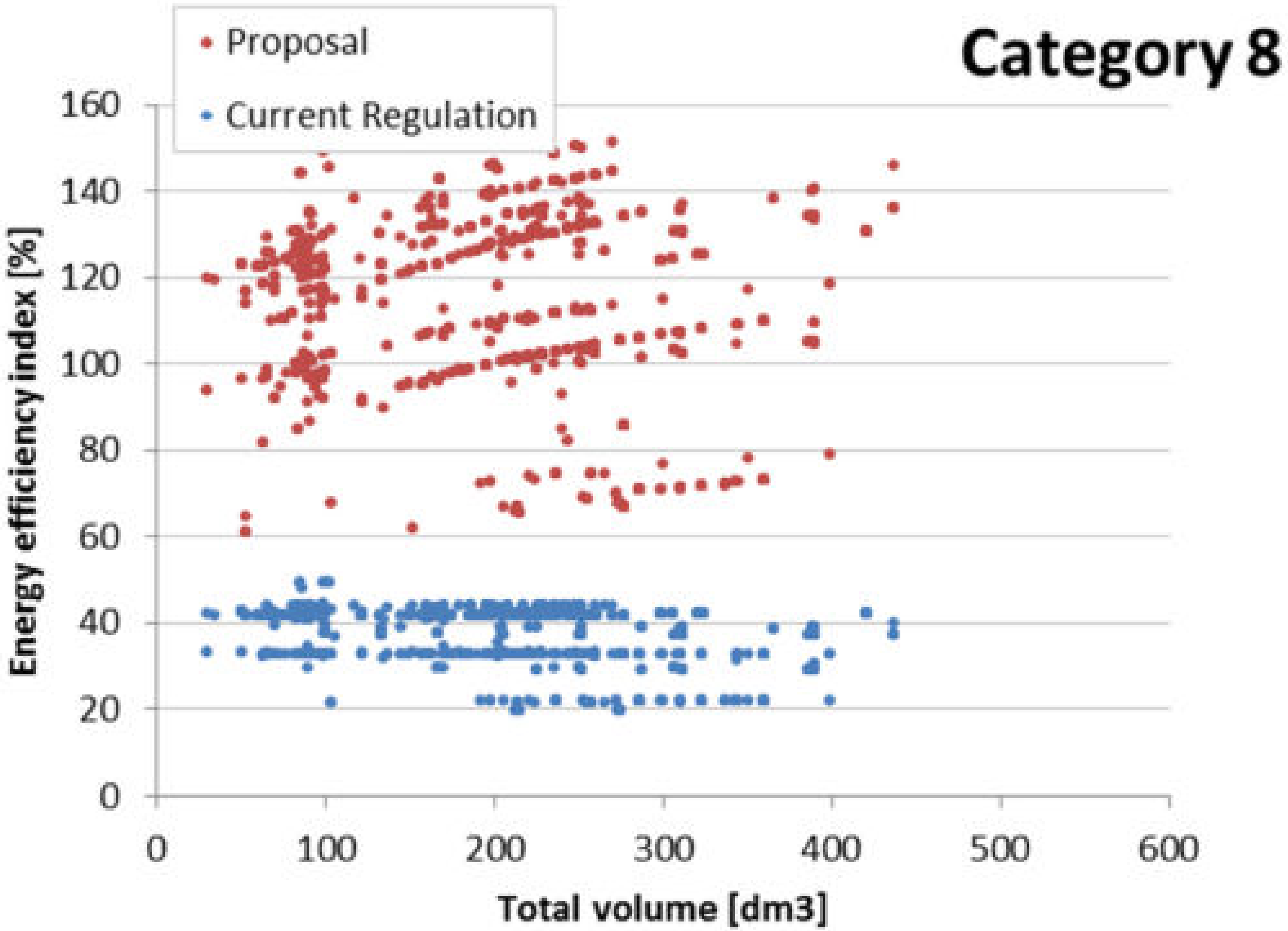
CECED comparison proposal vs. current EEI



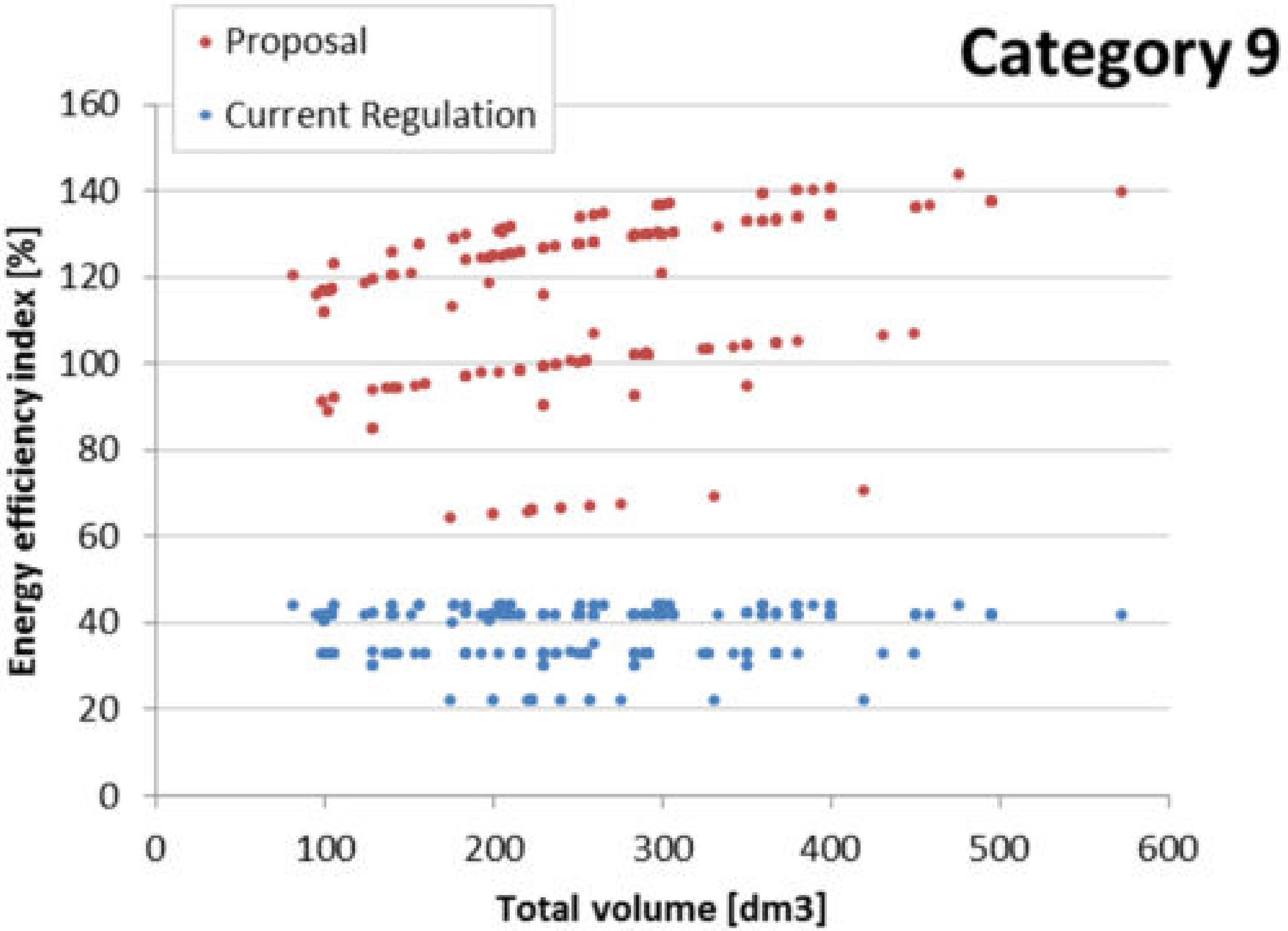
CECED comparison proposal vs. current EEI



CECED comparison proposal vs. current EEI



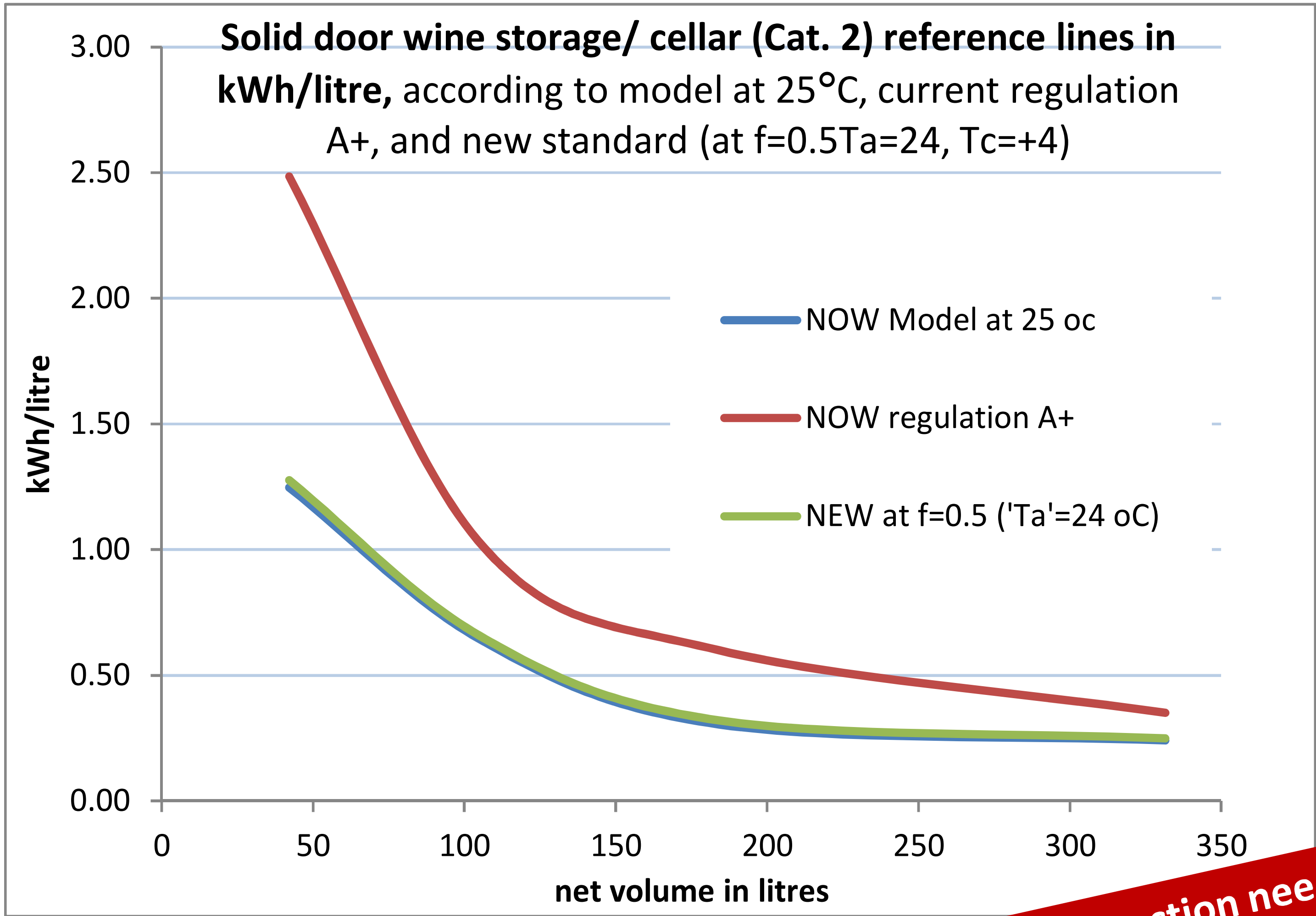
CECED comparison proposal vs. current EEI



Conclusions on proposal vs. current EEI

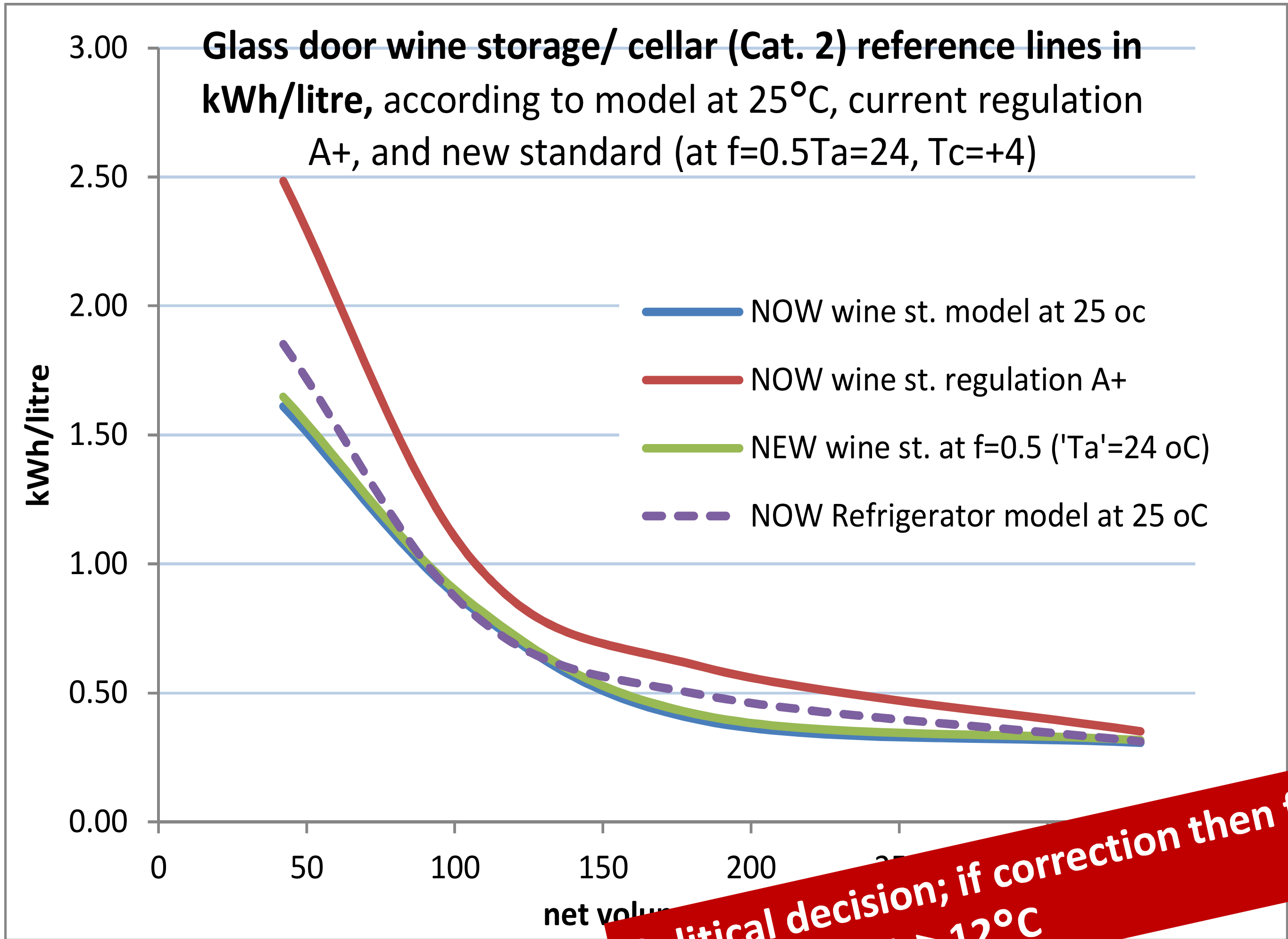
- Some relaxation for larger fridges, which is realistic given the low inclination of the reference line today, as indicated in the technical model.
- Somewhat more stringent requirements for large freezers.
- Chest freezers are relaxed compared to upright freezers, which is realistic given their lower energy consumption.
- The large combi appliances will have much more stringent requirement compared to the small ones, though less than in the analysis in the report.

Wine storage (Cat. 2) solid door



No correction needed

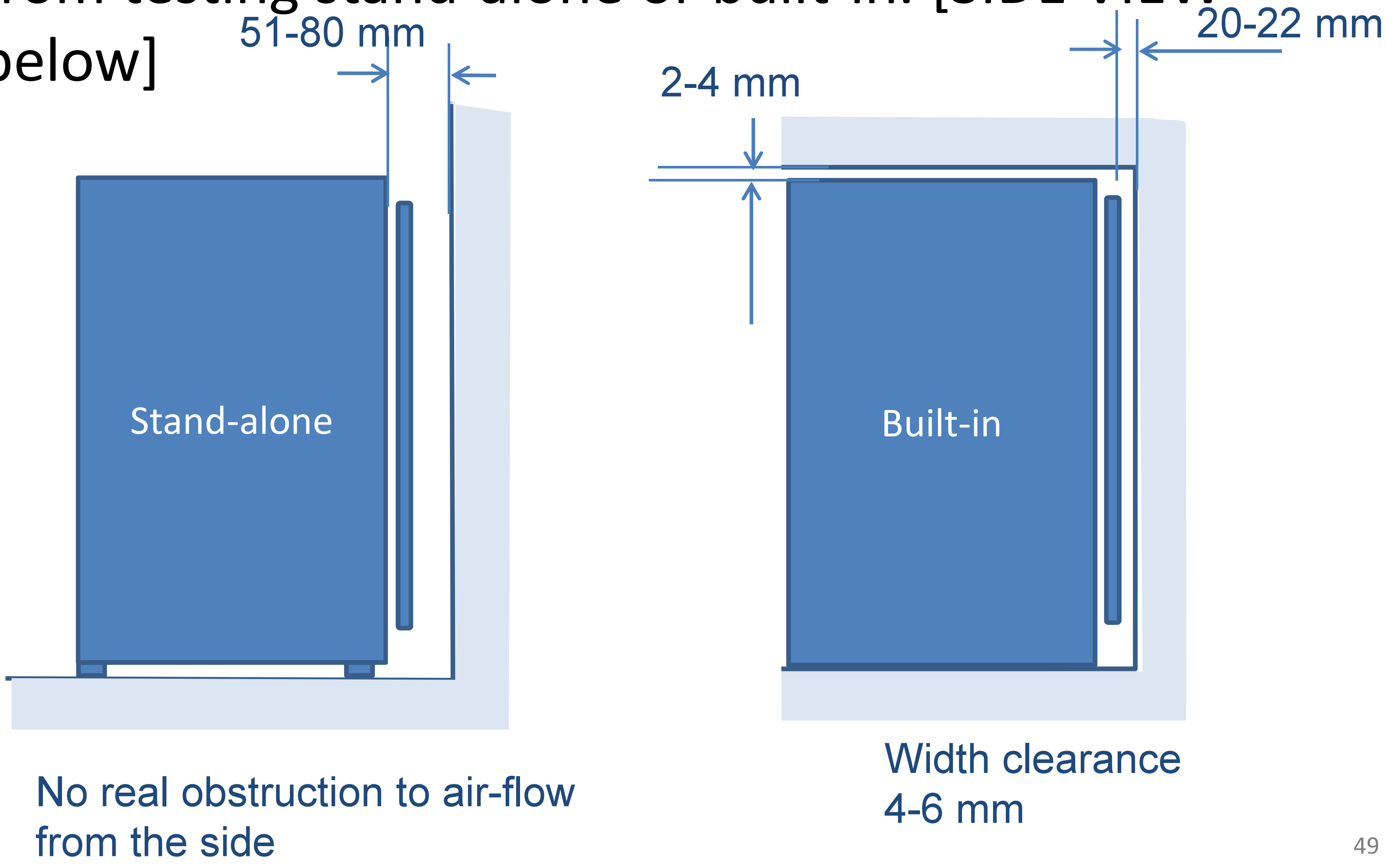
Wine storage (Cat. 2) glass door



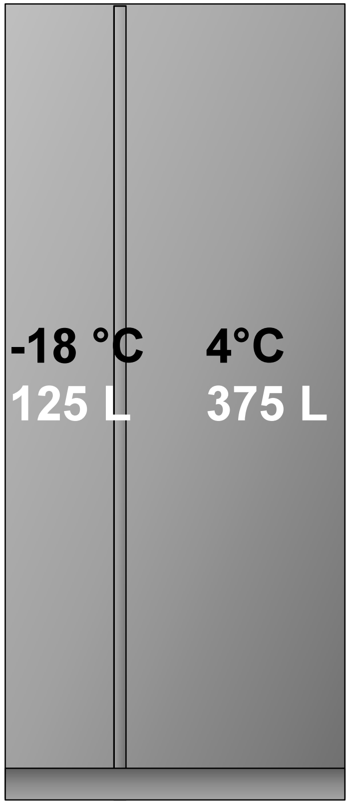
Political decision; if correction then factor ≤ 1.2 and only for $T_c \geq 12°C$

Built-in factor (proposed 1.1 for freezers, 1.04 for fridge)

- 8-10% difference in energy for the same appliance from testing stand-alone or built-in. [SIDE VIEW below]

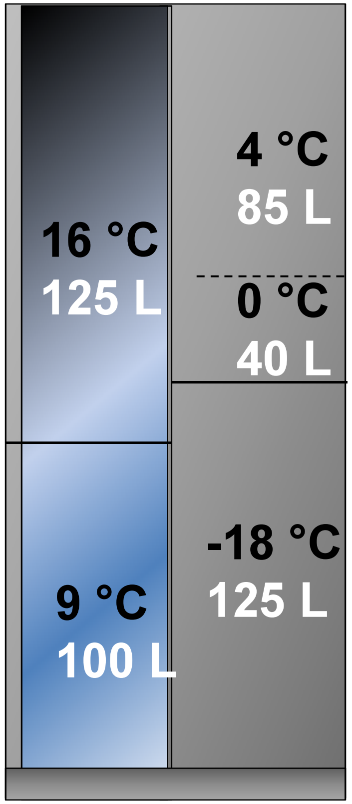


(multi-) Door compensation (2/3.5/5% for 3/4/>4 doors)



Healthier, tastier food & drinks
Less food waste
25-30% energy saving on cooling
10-12% energy saving total

The current metrics do not give a reward but implicitly a penalty (extra door losses)



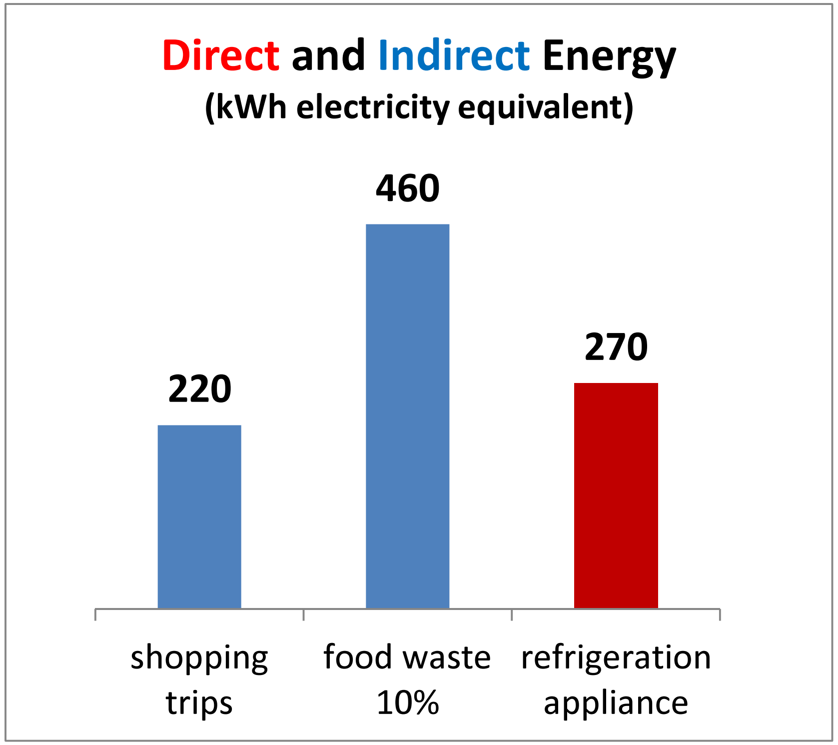
Estimated savings based on difference between compartment temperatures and 25 degree

Indirect energy: Food Waste & Shopping Trips

- Grocery shopping by car: Average 1-2 trips, 5-10 km per week → 500 km/year → city traffic 1 litre per 10 km→ 50 litre petrol/diesel → 2000 MJ primary/year → power generation 40%→ 220 kWh electricity/year equivalent

- Food 650 kg/yr/pp, 1500 kg/refrigeration appliance. Food life cycle energy content 25 MJ/kg* → 37500 MJ/refrigeration appliance → 4160 kWh electricity equivalent. Avoidable food waste in households (cooking failure, leftovers, spoil) 10%→ 416 kWh electricity equivalent.

- Compare: average refrigeration appliance 270 kWh electricity equivalent



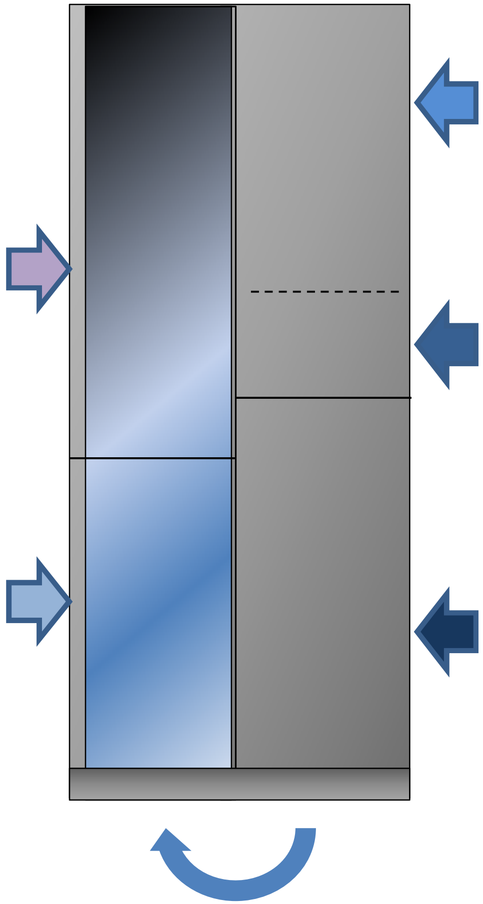
*=rough estimate based on Denmark 221 PJ, 9 Mt food. Source: Markussen, M., in *Energies* 2

Circular Economy: Fridge optimised to Reduce Food Waste

Optimal Food Storage & Preservation (illustrative)

PANTRY/CELLAR (16 °C, *humid or in containers, moderate ventilation)*
oranges, lemons, ripe tomatoes/ cucumbers/eggplant/melon/avocado /pineapple/mango/papaya/bananas, grapes, peaches & plumbs, apples & pears (separate ventilation --> ethylene),
potatoes (dark), red wine (dark), unopened cheese.

DRINKS/WINE STORAGE (8-10 °C)
white wine, beer, fruit juice, soft-drinks,
non-meat/fish leftovers, fruitcake , mayo/ketchup/salsa/honey (opened)



defrost cool re-use

FRIDGE
Fresh food (4 °C): Diary products (milk, yoghurt, eggs, cut & fresh cheese, pudding), green vegetables (salad, broccoli) & herbs, carrots, cold cuts (ham, salami,bacon), ready-meals & leftovers
Chill sub-compartment (0 °C): Fresh meat, poultry, fish, shellfish, etc.

FREEZER (-18°C):
frozen foodstuffs all types

derived from e.g. http://www.zentrum-der-gesundheit.de/obst-gemuese-lagern.html

Chapter 10 [Task 4.2]

Production, distribution, end-of-life

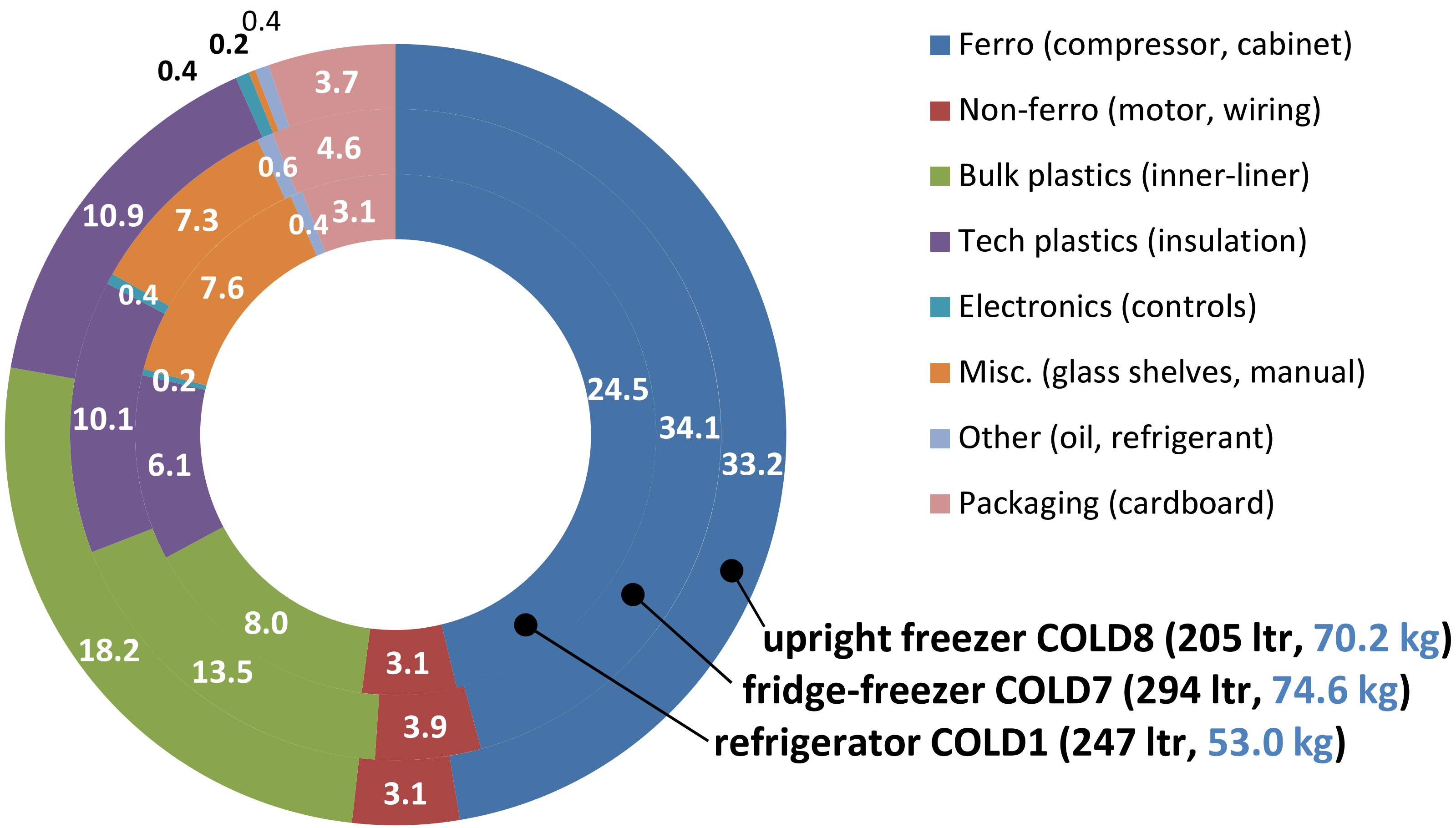
Average dimensions

Nr.	Category	pro-duct weight M	net int. volume V_{net}	gross int. volume V_{gross}	ext. height h	ext. width w	ext depth d	ext. volume V_{ext}	package volume (+8 cm overall)	rounded package volume V_{pack}
	unit	kg	dm^3	dm^3	cm	cm	cm	dm^3	dm^3	m^3
1	Refrigerator	50	247	254	135	57	59	454	827	0.9
2	Wine cooler	52.4	187	210	109	55	61	366	683	0.7
7	Fridge-freezer	70	294	334	170	62	63	664	1146	1.2
8	Upright freezer	66.5	205	230	148	63	63	587	1024	1.1
9	Chest freezer	47	261	268	86	106	69	629	1058	1.1

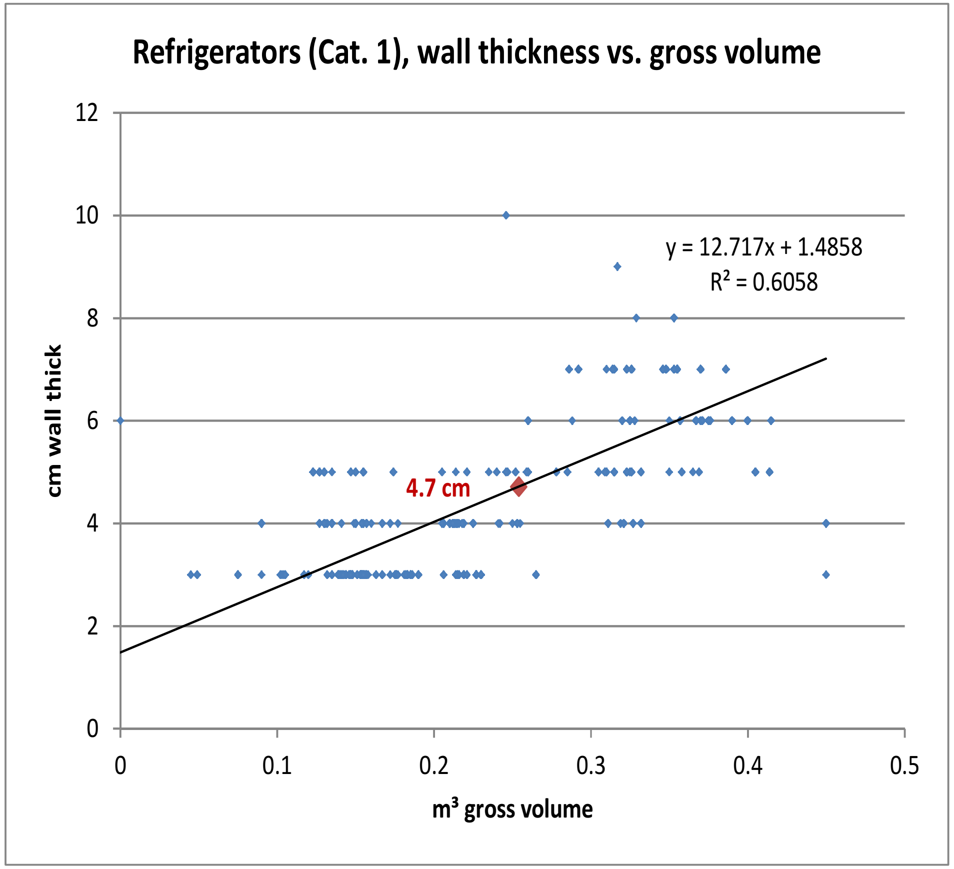
Fridge-freezer: 27% freezer (79 ltr.); 73% fridge (215 ltr.)

Also in report: External (compressor) and internal component space, average wall thickness, envelope surface, condenser surface, door gasket length.

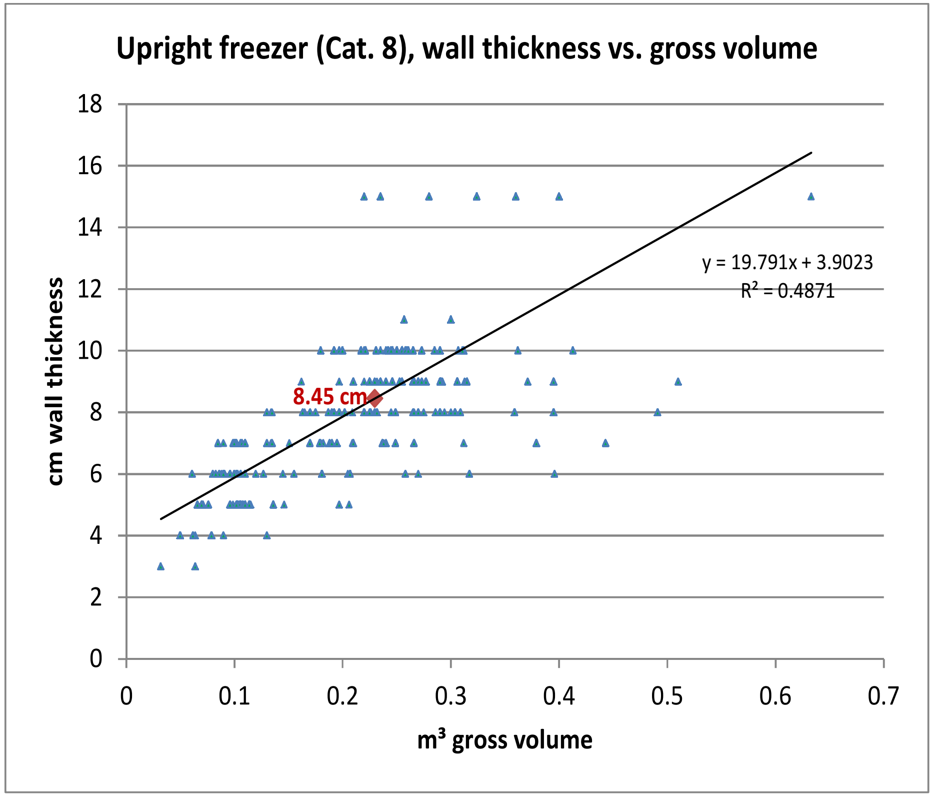
Bills of Materials (in kg/unit)

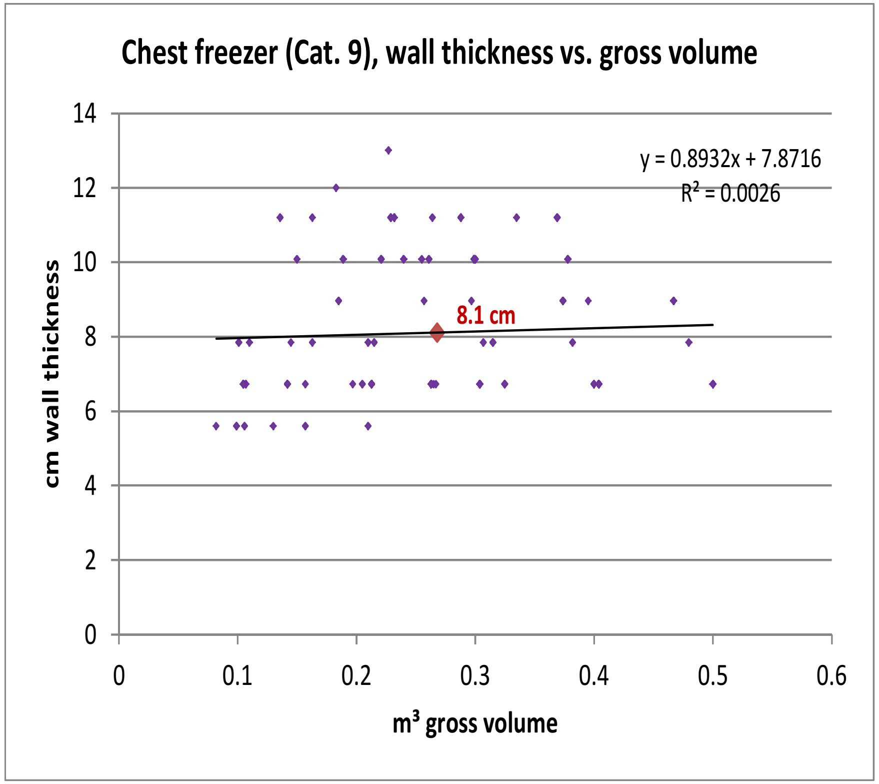


Wall thickness vs. Size, cat. 1 & 7



Wall thickness vs. Size, cat. 8 & 9

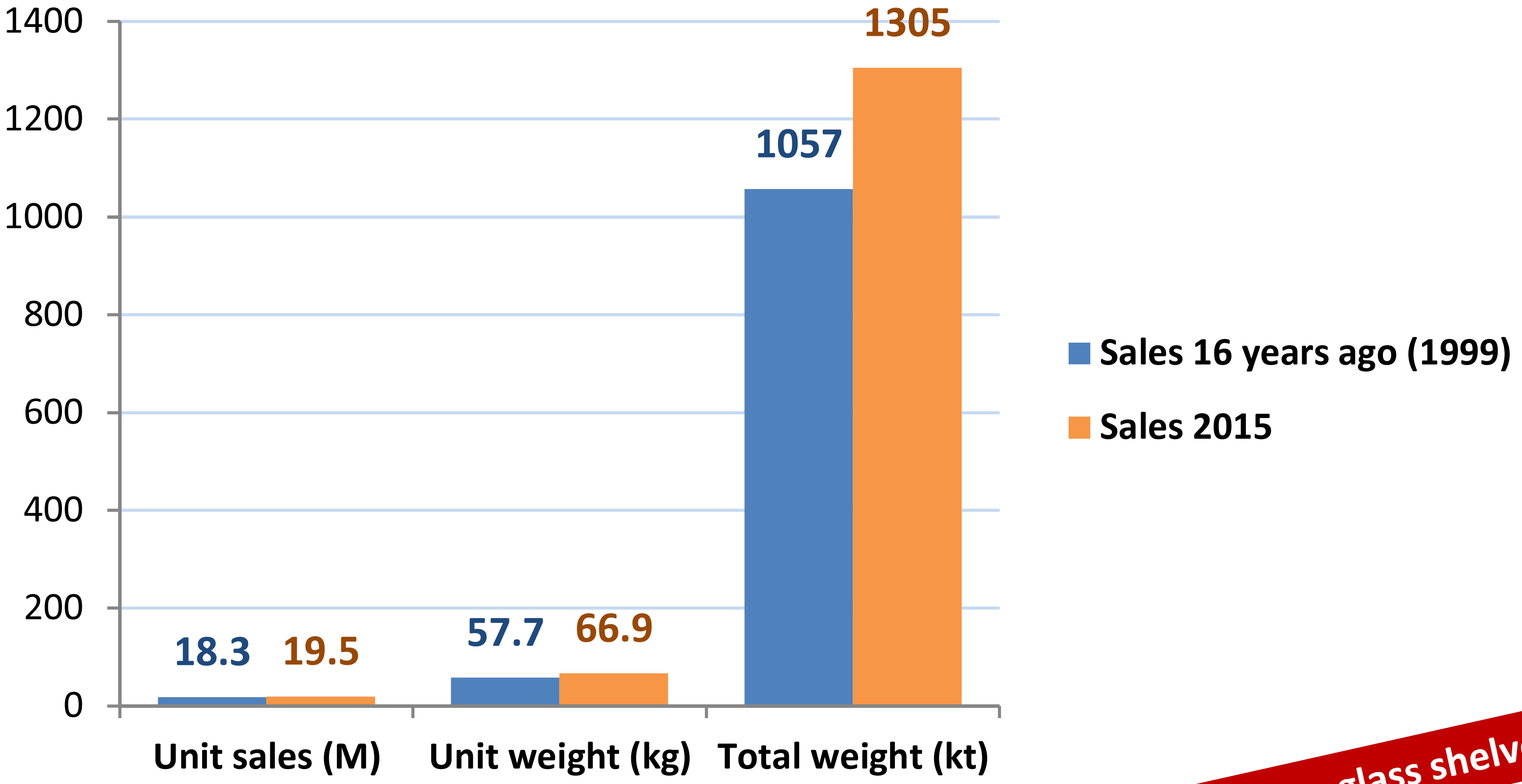




Chapter 11 [Task 5]

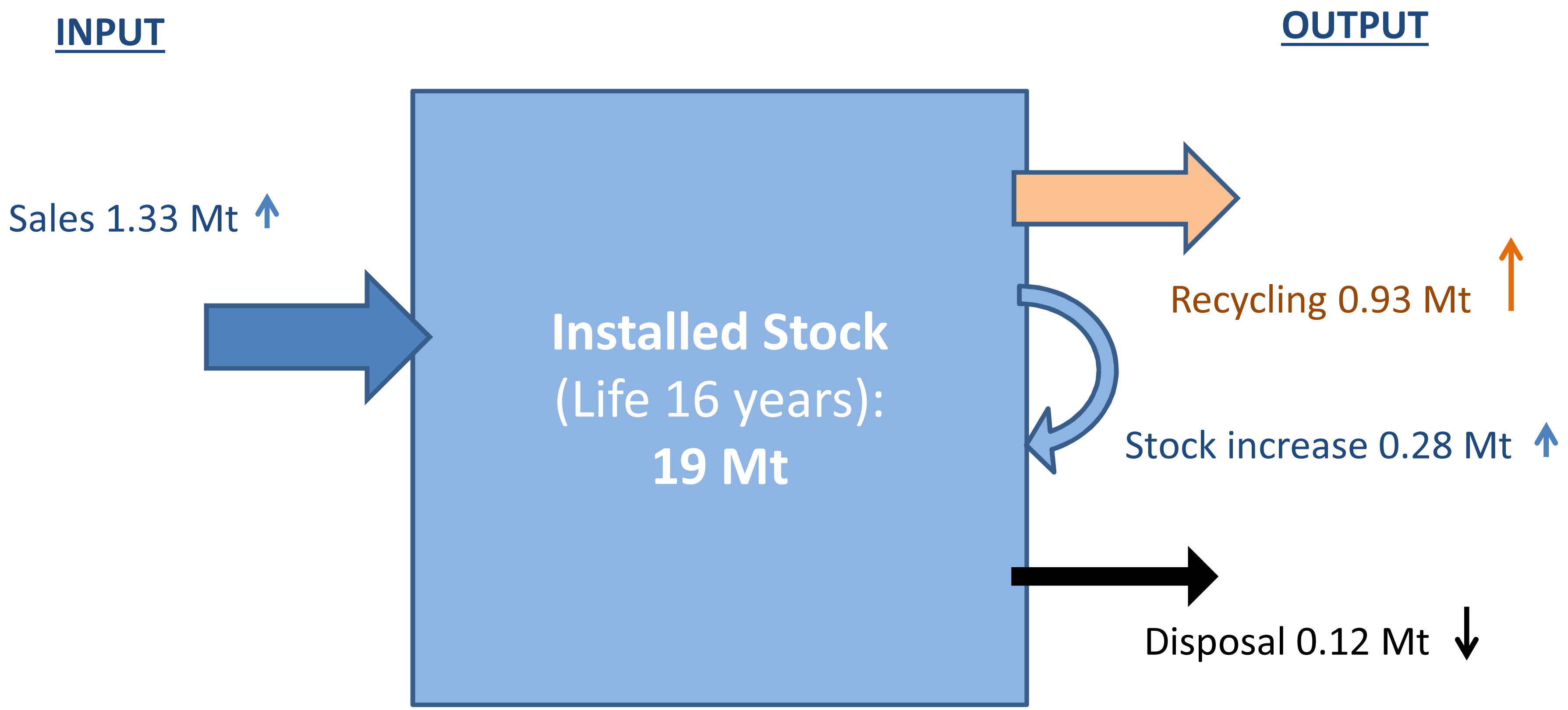
BaseCase environment & economics

Materials balance sales 1999-2015

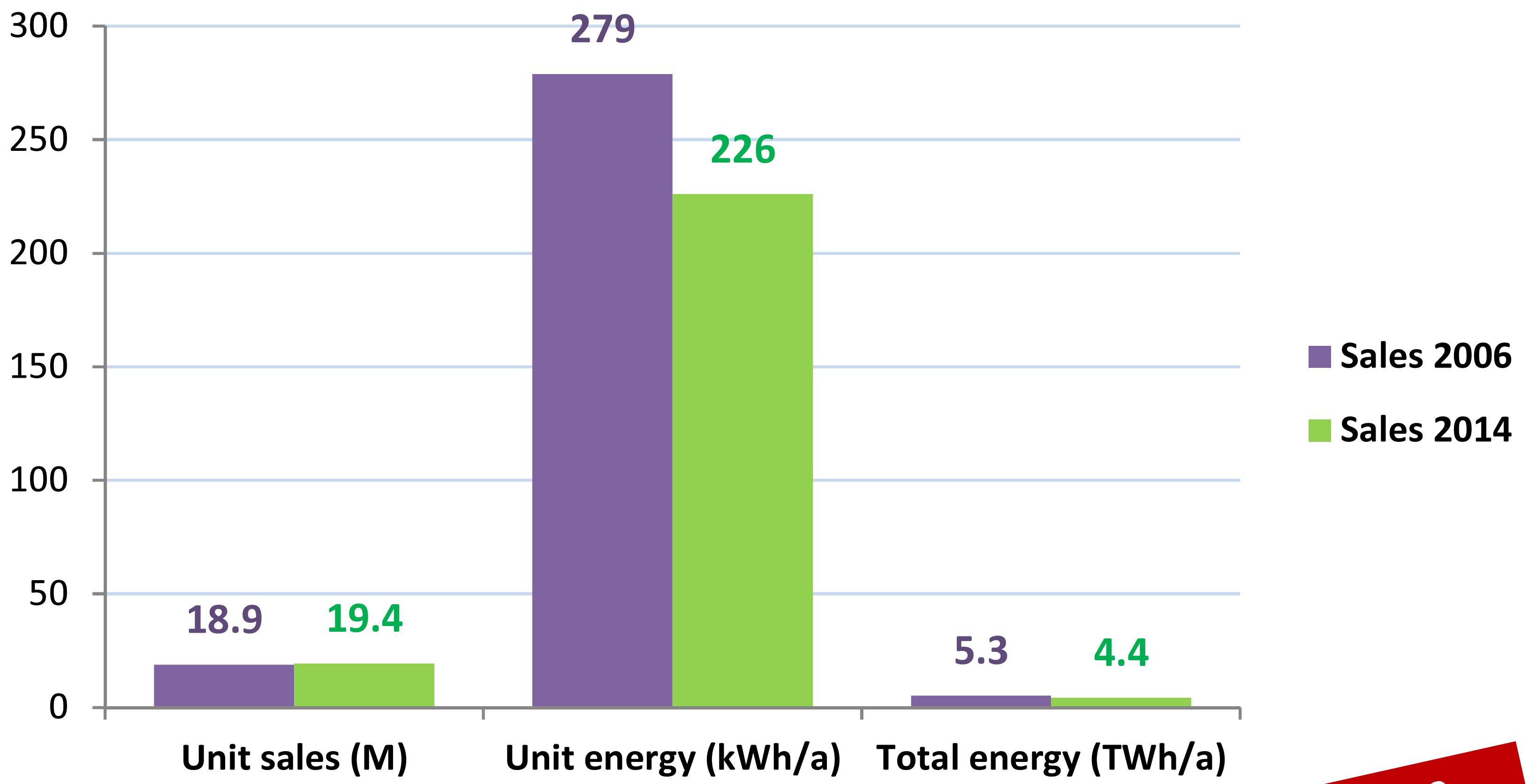


Larger + more insulation + more glass shelves

Materials flow 2014 (approx.)



Energy sales 2006 (average stock)-2014

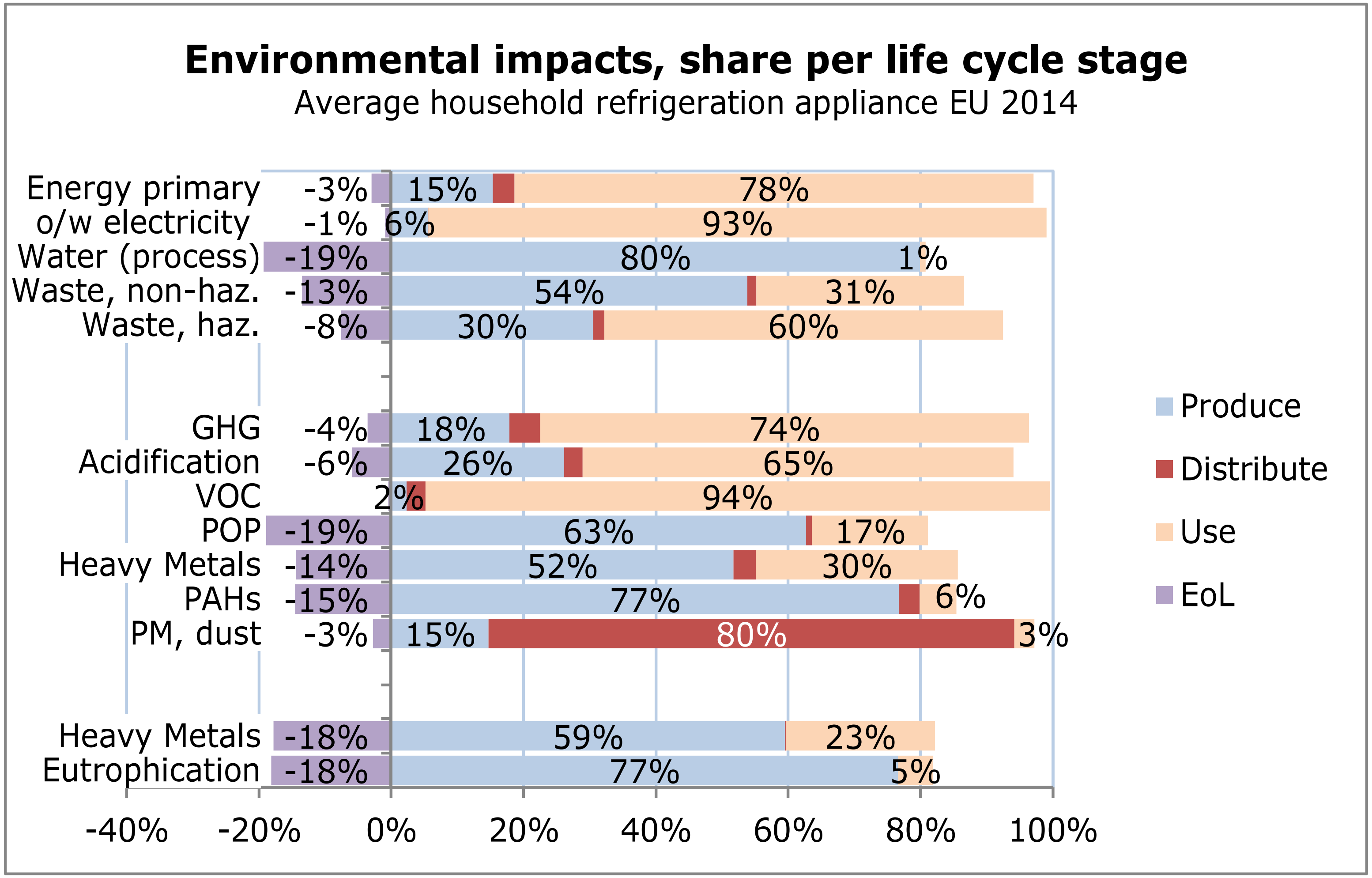


New/Stock energy ratio 0.82
(range 0.74-0.87 , depends on cat.)

Basecase Prices

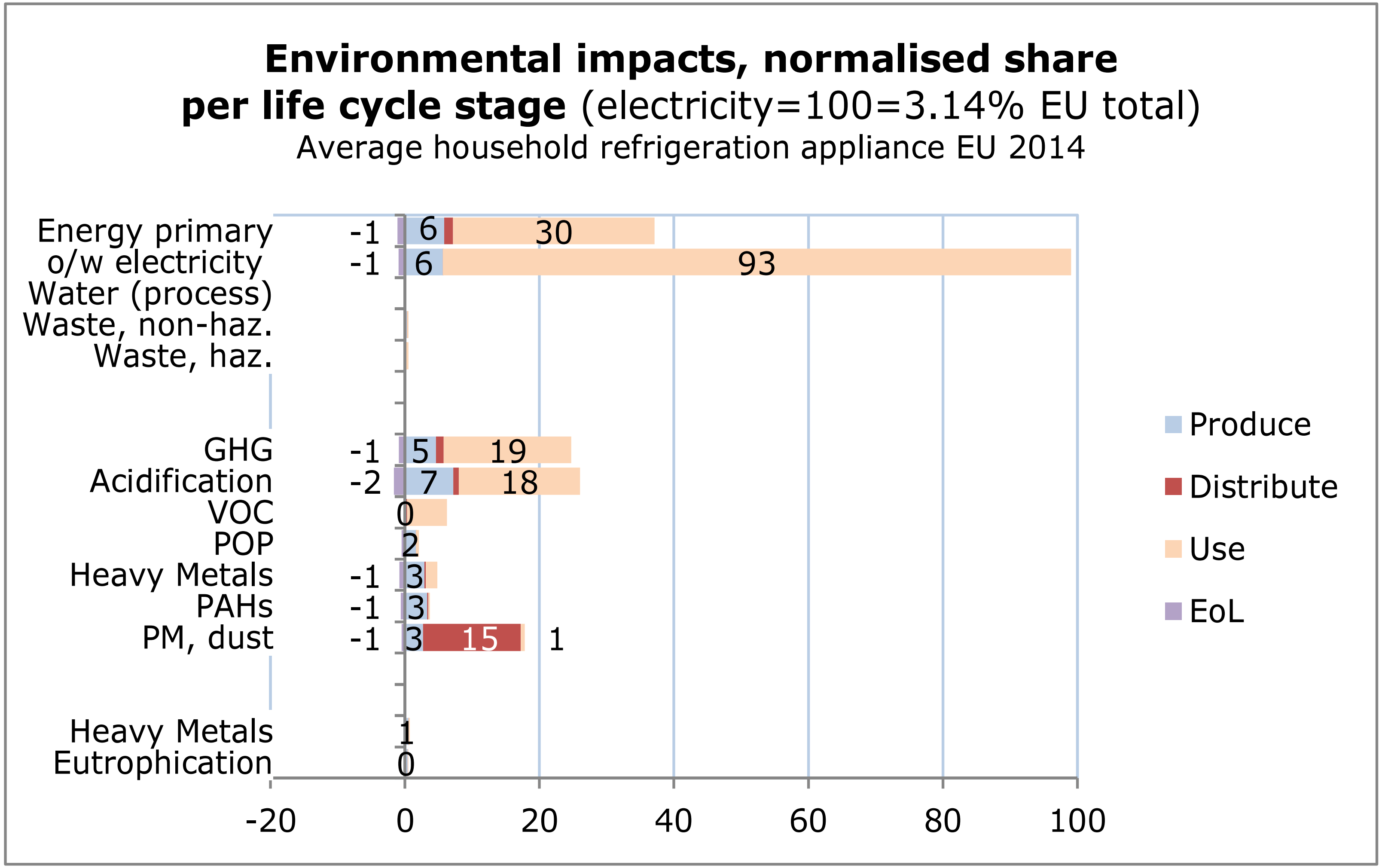
Base-case	Energy label class	energy	net volume	BI	FF	Unit price	cost of saving	price per litre	avg unit price	msp	ratio price/ msp	sales	A+ base price
		kWh/a	litre	%	%	euros	eur/ kWh	eur/L	euro	euro	-	million	euros
COLD1	A+	131	240	36%	9%	456	ref	1.9	**495**	202	2.5	3.6	420
	A++	105	257	50%	7%	514	2.2	2					
	A+++	71	271	36%	6%	623	3.2	2.3					
COLD2	B	206	198	0%	0%	792	7.8	4	**1344**	336	4	0.3	792
	A	150	193	0%	0%	1448	11.7	7.5					
	A+	124	289	0%	0%	2023	22.1	7					
	A++	111	512	0%	0%	3072	80.7	6					
COLD7	A+	301	319	18%	52%	520	ref	1.63	**557**	231	2.4	11.5	466
	A++	226	296	32%	38%	574	0.7	1.94					
	A+++	154	310	32%	26%	682	1.5	2.2					
COLD8	A+	253	183	33%	48%	366	ref	2	**439**	217	2	1.4	320
	A++	218	219	16%	66%	482	3.3	2.2					
	A+++	168	289	0%	71%	751	5.4	2.6					
COLD9	A+	256	264	0%	1%	343	ref	1.3	**356**	215	1.7	2.6	343
	A++	194	255	0%	0%	370	0.4	1.45					
	A+++	126	241	0%	0%	482	1.7	2					
Sales weighted average									**522**	**224**	**2.31**	**19.4**	**435**

Environmental impacts, share per life cycle stage



Environ. impacts, share of EU-total

(electricity= 100= 3.4% of EU-total)



Average Life Cycle Costs (new unit 2014, in euro/unit)

	COLD1	COLD2	COLD7	COLD8	COLD9	TOTAL
Product Price	495	1344	557	439	356	528
Electricity	433	777	850	666	787	714
Total consumer	**928**	**2121**	**1407**	**1105**	**1143**	**1240**
Total external costs	131	158	204	153	179	178
Total societal costs	**1059**	**2279**	**1611**	**1258**	**1322**	**1418**

Monetary Life Cycle Costs, for consumer plus external costs, per NEW unit: purchase and discounted running costs over Life (16 years) [discount rate 4%; electricity tariff escalation rate 4%]

EU Consumer expenditure & external costs 2014

(in **billion** euros)

	COLD1	COLD2	COLD7	COLD8	COLD9	TOTAL
Product Price	1.8	0.4	6.5	1.1	0.5	10.3
Electricity	2.1	0.3	11.0	2.0	1.8	17.1
Total consumer	**3.8**	**0.7**	**17.5**	**3.1**	**2.3**	**27.4**
Total external costs	0.5	0.1	2.5	0.4	0.3	3.8
Total societal costs	**4.4**	**0.7**	**20.0**	**3.5**	**2.6**	**31.2**

External costs ('Societal life cycle costs') are calculated with the MEErP EcoReport tool.
Explained in the MEErP, Part 1, Paragraph 7.6 and based on a publication by the European Environmental Agency (EEA, Revealing the costs of air pollution, Technical Report No. 15/2011, Copenhagen, Nov. 2011). Amongst others it looks at the costs of CO2 abatement (based on emission trading prices) and monetary indicators for extra health care costs from emission of pollutants.

Chapter 12 [Task 6]

Design options

Base cases

Basecase	Energy label class	energy	net volume	Main Climate Class
		kWh/a	*litre*	
COLD1	A+	114	250	SN-T
COLD2	B	167	224	N
COLD7	A+	257 [237 (2T) / 280 (1T)]	309	SN
COLD8	A+	233	205	SN
COLD9	A+	236	261	SN-T

(CECED comments COLD2, COLD7 and COLD8 base case)
EEI values in the report are indicative / analysis is led in terms of energy consumption.
Indicated EEI values should be corrected.

Identification of main technical characteristics of base cases

- Same model as in Task 4, geometry and calculations
- For base cases; av. insulation level known but not compressor COP and temperature difference at heat exchangers
- Identification of these 3 main parameters for the base cases
- Cat 7: CECED COMMENT TO BE DISCUSSED
  - 2T vs 1T -> Solenoid valve, parallel circuitry, larger evaporator surface, Tev_refrigerator = - 15 °C (Tev_freezer= -28 °C) (Ref. 1&2)
  - Heat load equally shared between Refrigerator and freezer

Identification of main technical characteristics

Base case		COLD1	COLD2	COLD8	COLD9
Vrf	refrigerated volume (m^3)	0,250	0,224	0,203	0,260
	refrigerated volume (litres dm^3)	250	224	203	260
t	average wall thickness (m)	0,050	0,020	0,085	0,080
Tc	compartment temperature (°C)	5	12	-20	-20
Umisc	heat transfer coefficient door gasket and misc. load (W/mK)	0,080	0,080	0,030	0,030
ΔTev	evaporator temperature difference (K)	17	22	10	10
ΔTcd	condenser temperature difference K	10	13	12	12
COPnom	nominal at -23.3/54.4°C, sub-cooling 32.2°C	1,644	1,53	1,62	1,655
Pnom	Nominal compressor cooling power (W)	63	63	141	141
Cool. Load Ratio	Ratio of heat load to cool power	26%	33%	38%	40%

Identification of main technical characteristics

Base case		COLD7
Vrf	refrigerated volume (m^3)	0,309
	refrigerated volume (litres dm^3)	309
t	average wall thickness (m)	0,055
Tc	compartment temperature (°C)	-2,5
Umisc	heat transfer coefficient door gasket and misc. load (W/mK)	0,080
Δtev_r	Refrigerator evaporator temperature difference (K)	20
Δtev_f	Freezer evaporator temperature difference (K)	8
ΔTcd_r	Refrigerator condenser temperature difference (K)	15
ΔTcd_f	Freezer condenser temperature difference (K)	10
Pnom	Nominal compressor cooling power (W)	141
COPnom	nominal at -23.3/54.4°C, sub-cooling 32.2°C	1,54
COP	Average COP (supposing the load is equally shared between refrigerator and freezer)	2,1
Cool. Load Ratio	Ratio of heat load to cool power (ave. of freezer and evaporator load)	31%

CECED comment to be discussed

The volume of the base case model could not be confirmed with the model used in chapter 9. Following this model the volume should have been 297 dm3.

Design options

- Compression C1, C2, C3, VSD:
  - Better COP (3 options depending on size, 1.72, 1.85 and 1.98)
  - VSD (1 point with reduced flow 30 W with a COP of 1.5, and a COP of 1.85 for minimum capacity above 60 W)
- Better insulation I1, I2, I2, I3, I4, I5:
  - +1, +2, +3 cm insulation thickness / Base case level
  - VIP cov. 70 % door area, 50 % cabinet walls
  - CECED: I3 may be difficult to reach (platform issue over 100 mm) + insulation superior to optimal insulation level (85 mm)
- CECED: comment to be discussed on VIP (« The effect of the vacuum panel insulation depends on the wall thickness of the appliance, where the effect is smaller the thicker the PU insulation. This seems to be taken properly into account in the model in the report.”)

Design options

- Better insulation D1, D2:
  - Wine cooler glass door U value:
  - BC U=1.7 W/(m2.K), D1=1.3 and D2=0.8 (triple glazing krypton filled)
  - CECED: possible intermediary option with argon triple glazing Uvalue 1.1
- PCM:
  - Longer times means lower cycling impact (degradation divied by 2)
  - Small increase in evaporating and condensing temperature
  - CECED: difficult to implement but considered in their analysis + volume reduction of PCM not included (to be done)

Design options

- Heat exchanger improvement
  - Limited space for heat exchange surface increase (in general)
  - F1: Improved indoor heat transfer by adding convection fan +40 % VS natural convection with 0.8 W fan (Ref. 3); solution includes improved multiflow design
  - F2: Improved outdoor heat transfer on wire and tube condenser +40% with 0.7 W fan

  - *CECED comment on F1: volume reduction of fan not included (to be done) ; not an efficient option for highly insulated models (negative effects included afterwards)*
  - *CECED comment on F2: reliability issue. Possible negative effect with VSD ; this is included in the evaluation afterwards.*

Environmental impact

- Main environmental impact energy
- Insulation improvement: reduces heat load, slight change on load ratio (cycling)
- Compressor efficiency improvement: direct impact on consumption, except in case of oversizing
- VSD: increase of the evaporator temperature, condenser change depends on HX capacity
- Improvement of heat transfer capability, reduction of temperature differencees across heat exchangers

Environmental impact

- Simplified model adopted to compute Tev and Tcd for design options:
  - Heat exchanger nominal size calculation
  - Heat balance at evaporator side :
    - P(Tev,Tcd) = Uev(Tev).A.(Tev-Tc)
    - U(Tev): heat transfer correlation
  - Pcond=P(1+1/COP)
  - Heat balance
    - Pcond = Ucd(Tcd).A.(Tcd-Tair)
    - U(Tcd): heat transfer correlation

Environmental impact of individual options - compression

Option	Description	COLD 1	COLD 2	COLD 7	COLD 8	COLD 9
C1	Compressor nominal COP improvement	5%	11%	11%	6%	3%
C2	Compressor nominal COP improvement	11%	17%	17%	13%	10%
C3	Compressor nominal COP improvement	6%	14%	22%	19%	16%
VSD	Variable frequency drive	11%	21%	32%	27%	28%

Corrected VSD gain (at equal COP)

	COPnom	COP VSD	Gain VSD (at equal COPnom)
COLD1	1,64	1,50	18%
COLD2	1,53	1,50	23%
COLD7	1,54	1,85	18%
COLD8	1,62	1,85	16%
COLD9	1,66	1,85	19%

- Required compressor oversizing reduces gain of C3 for refrigerator.
- VSD gain varying between 16 and 23 %

Environmental impact of individual options - insulation

Option	Description	COLD1	COLD2	COLD7	COLD8	COLD9
I1	Increased insulation thickness	14%	19%	15%	7%	7%
I2	Increased insulation thickness	25%	33%	25%	12%	13%
I3	Increased insulation thickness	34%	39%	34%	16%	18%
I4	Use of vacuum insulated panels, 70 % of door are covered	8%	NA	8%	7%	5%
I5	Use of vacuum insulated panels, 50 % of lateral and back sides covered	18%	15%	16%	15%	15%

- The thicker the insulation, the lower the effect of increasing insulation.
- COLD 9 has a different geometry -> different results.
- Insulation gains I1 to I5 are overestimated by max about 15% (mistake to be corr. in next version), ie 12.5% versus 14% for COLD1-I1 option (in line with CECED comments)
- *CECED comment : « Increasing the insulation is generally not possible in all outward directions as is done in option I1, I2 and I3, given certain standardisation in depth and width direction (e.g. width of 59 and 69 cm are typical). The more realistic approach is to increase the height to compensate the get back the original volume. However, the effect on the calculation results will be small.»*

Environmental impact of individual options 3/3

Option	Description	COLD1	COLD2	COLD7	COLD8	COLD9
D1	Glass door double glazing E-coating, krypton fill	NA	7%	NA	NA	NA
D2	Glass door triple glazing E-coating, krypton fill (heavy door)	NA	17%	NA	NA	NA
PCM	Phase change material (water for refrigerator or water and ammonium chloride solution for freezer)	4%	4%	4%	4%	3%
F1	Improved convection heat transfer with indoor fan and multiflow	3%	3%	3%	1%	0%
F2	Improved condenser heat transfer with outdoor fan	4%	5%	4%	4%	NA

- F1 only applied to fridge for COLD7
- F2 not applied to COLD9 – not clear if this would have a positive effect
- F1 and F2 small gains overall.

Economic evaluation – base cases

Base case	energy	net volume	avg unit price	msp	ratio price/ msp
	kWh/a	*litre*	euros	euros	-
COLD1	114	250	495	202	2,5
COLD2	167	224	1344	336	4,0
COLD7	257 [237 (2T) / 280 (1T)]	309	557 [569 (2T) / 545 (1T)]	231 [236 (2T) / 226 (1T)]	2,4
COLD8	233	205	439	217	2,0
COLD9	236	261	356	215	1,7

- Hypothesis inherited from the market analysis
- Very different product prices and MSP
- Simplified engineering cost model to represent the MSP and compute the impact of design options

Economic evaluation – simplified engineering model

COMPONENTS	UNITARY PRICE (per unit, m, kg, liter) x Quantity	MULTIPLIER 1	MULTIPLIER 2
COLD CIRCUIT			
	Compressor		F_OEM
	Evaporator(s) / aspiration storage volume		F_MANUF
	….		….
CABINET, INSULATION, DOOR, GASKET, SHELVES GLASSES …			
	Cabinet / door steel sheet		F_MANUF
	Insulation PUR cyclopentane		F_MANUF
	….		….
ELECTRIC			
	Lamp LED 1 to 1,5 W	FINISH	F_OEM
	Door lamp switch	FINISH	F_OEM
	….	….	….
	TOTALS	Components	Overheads, margin …
	Manufacturer selling price		
	Base case price		

Economic evaluation – simplified engineering model

	COLD1	COLD2	COLD7	COLD8	COLD9
F_OEM	1,37	1,67	1,31	1,21	1,37
F_MANUF	2,50	3,05	2,00	1,67	2,00
FINISH	1,66	3,50	1,66	1,00	1,00
Total component / raw material value in Euros	111	139	147	150	124
Total component / raw material value in % of MSP	55%	41%	62%	69%	58%
Overhead, energy, labor … in Euros	91	197	89	67	91
Overhead, energy, labor … in % of MSP	45%	59%	38%	31%	42%
Manufacturer selling price (MSP)	202	336	236	217	215

Economic evaluation – Costing of design options

- Compression:
    - 10 USD for 0.3 point improvement in nominal COP – ref value 1.54
    - VSD: compressor cost +50% (cost probably overestimated)
- Insulation:
    - Qty of foam (price by volume)
    - VIP, 20 USD/m2. Same volume of foam discounted (cost probably overestimated)
    - Overcosts from Ecodesign study on windows. CECED comment: other values given for overcost of glass door options
- PCM:
    - Cost per kg of PCM required from Lit. 0.45 USD/kg
- Heat exchangers:
    - About 2 Euros / fan + multiflow for F1 option

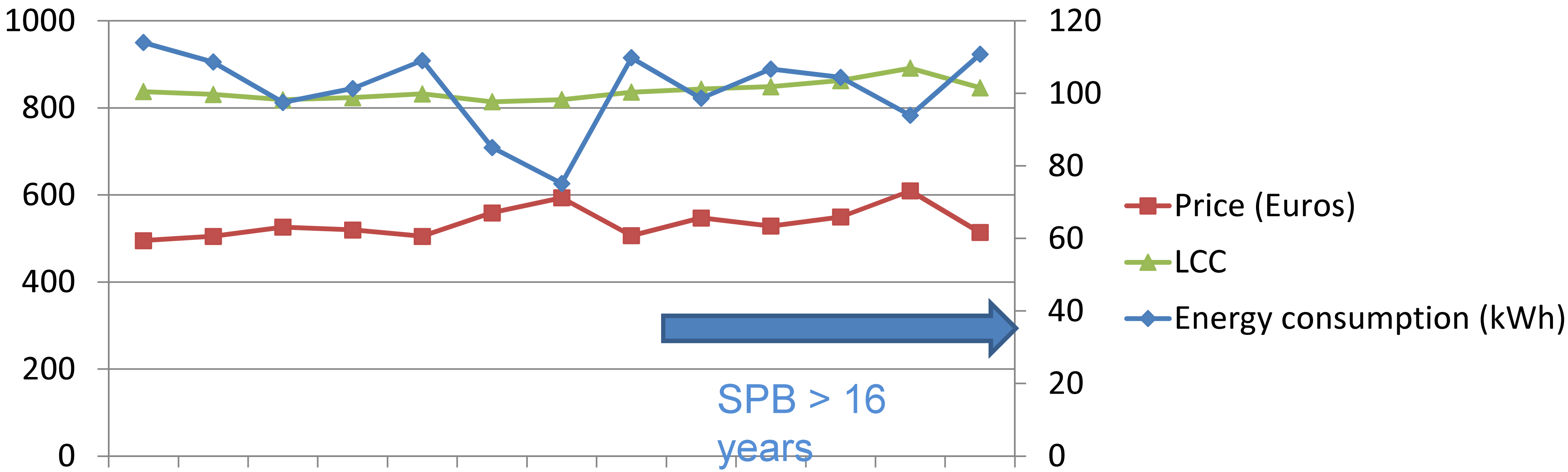
Economic evaluation – Costs of individual options

Option	COLD1	COLD1	COLD2	COLD2	COLD7	COLD7	COLD8	COLD8	COLD9	COLD9
	Euros	**%**	**Euros**	**%**	**Euros**	**%**	**Euros**	**%**	**Euros**	**%**
	495		**1344**		**569**		**439**		**356**	
C1	10	2%	39	3%	21	4%	11	2%	5	1%
C2	24	5%	64	5%	35	6%	23	5%	13	4%
C3	33	7%	82	6%	49	9%	36	8%	22	6%
VSD	43	9%	90	7%	135	24%	129	29%	102	29%
I1	31	6%	70	5%	31	5%	25	6%	16	4%
I2	64	13%	228	17%	64	11%	52	12%	33	9%
I3	98	20%	399	30%	98	17%	79	18%	51	14%
I4	54	11%	NA	NA	29	5%	36	8%	20	6%
I5	114	23%	125	9%	76	13%	79	18%	58	16%
D1	NA	NA	1	0%	NA	NA	NA	NA	NA	NA
D2	NA	NA	97	7%	NA	NA	NA	NA	NA	NA
PCM	10	2%	11	1%	8	1%	9	2%	10	3%
F1	14	3%	12	0,9%	16	3%	12	3%	5	1%
F2	7	1%	44	3%	5	1%	6	1%	NA	NA

LCC calculations

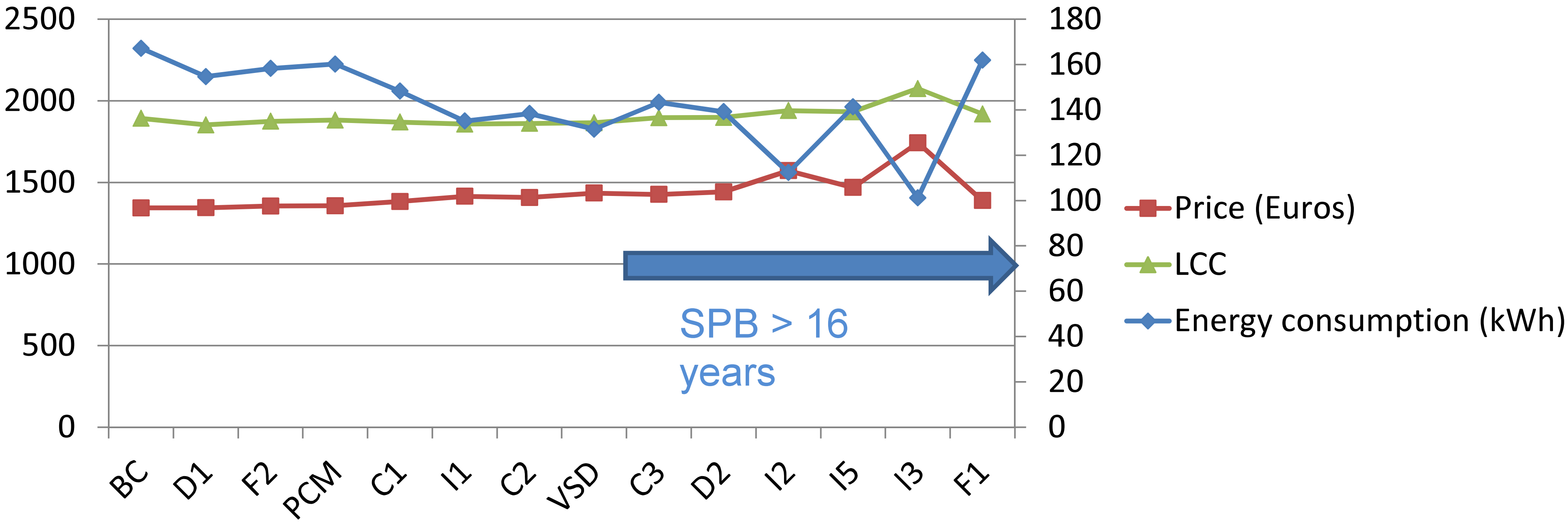
- No maintenance costs. There are probably minor reparation costs but these are low and not variable with any of the design options considered. Their impact on the evaluation of the design options is thus null.
- No end-of-life cost (this is supposed to be included in the product price).
- Electricity rate from Task 2: 0.205 euro / kWh
- Lifetime of the units: 16 years
- In addition, as suggested in the MEErP, it is supposed that the LCC can be calculated as: LCC= PP + N*OE + EoL
  - With PP: the purchase price; N: the lifetime of the unit; OE: the electricity expenditure; EoL in our case, the end of life fee, integrated into the product price.

LCC of individual options – COLD1, LCC Vs KWh.y



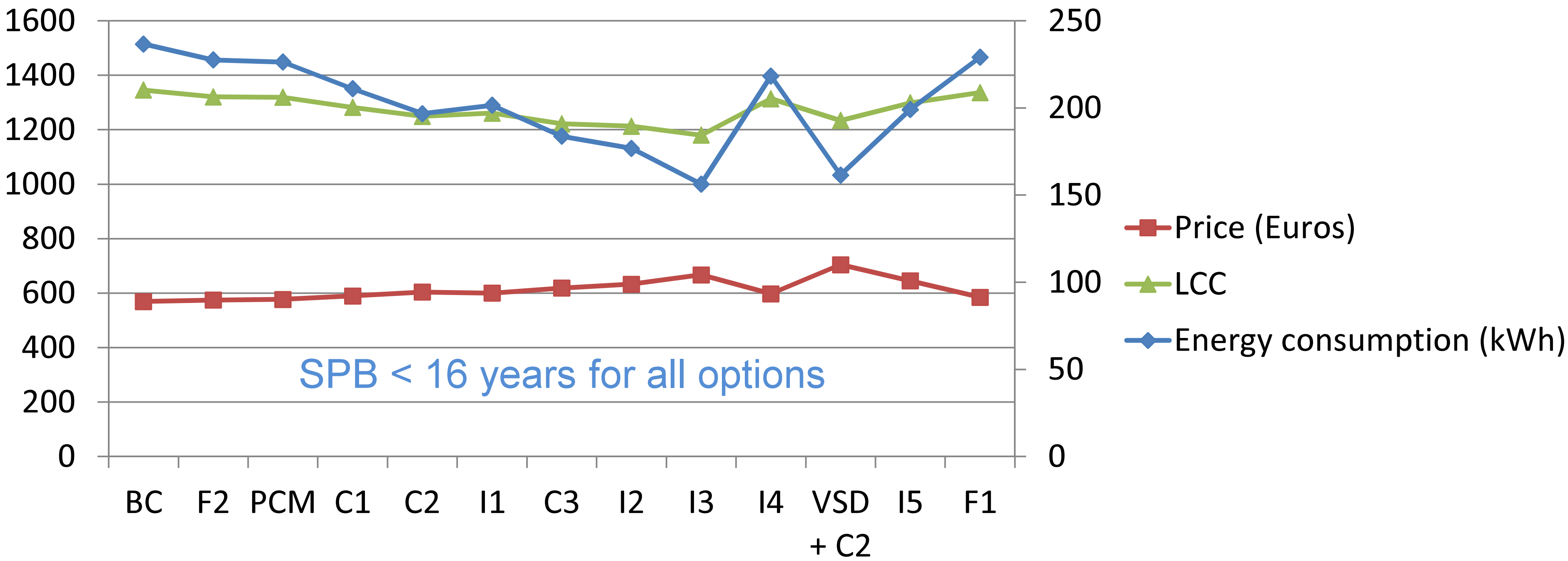
- SPB ranging from 9 years to 29 years
- Relatively low energy consumption gives large SPB

LCC of individual options – COLD2, LCC Vs KWh.y



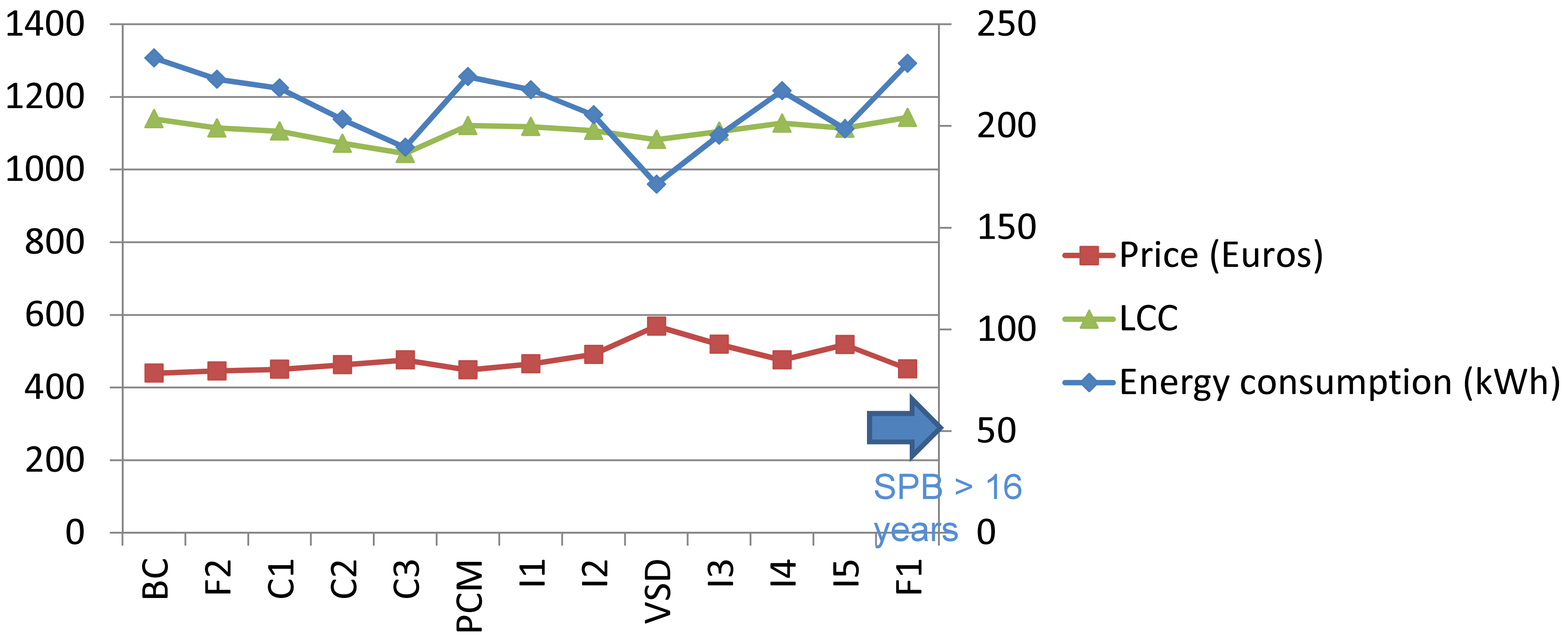
- SPB ranging from 0.3 (D1) years to 41 years (F1)
- Relatively low energy consumption gives large SPB except fot D1 (very low overcost)
- CECED main comment: on door options

LCC of individual options – COLD7, LCC Vs KWh.y



- SPB ranging from 3 (F2) years to 10 (F1) years
- Relatively large energy consumption gives smaller SPB

LCC of individual options – COLD8, LCC Vs KWh.y



- SPB ranging from 3 years to 22 years
- Relatively large energy consumption gives smaller SPB

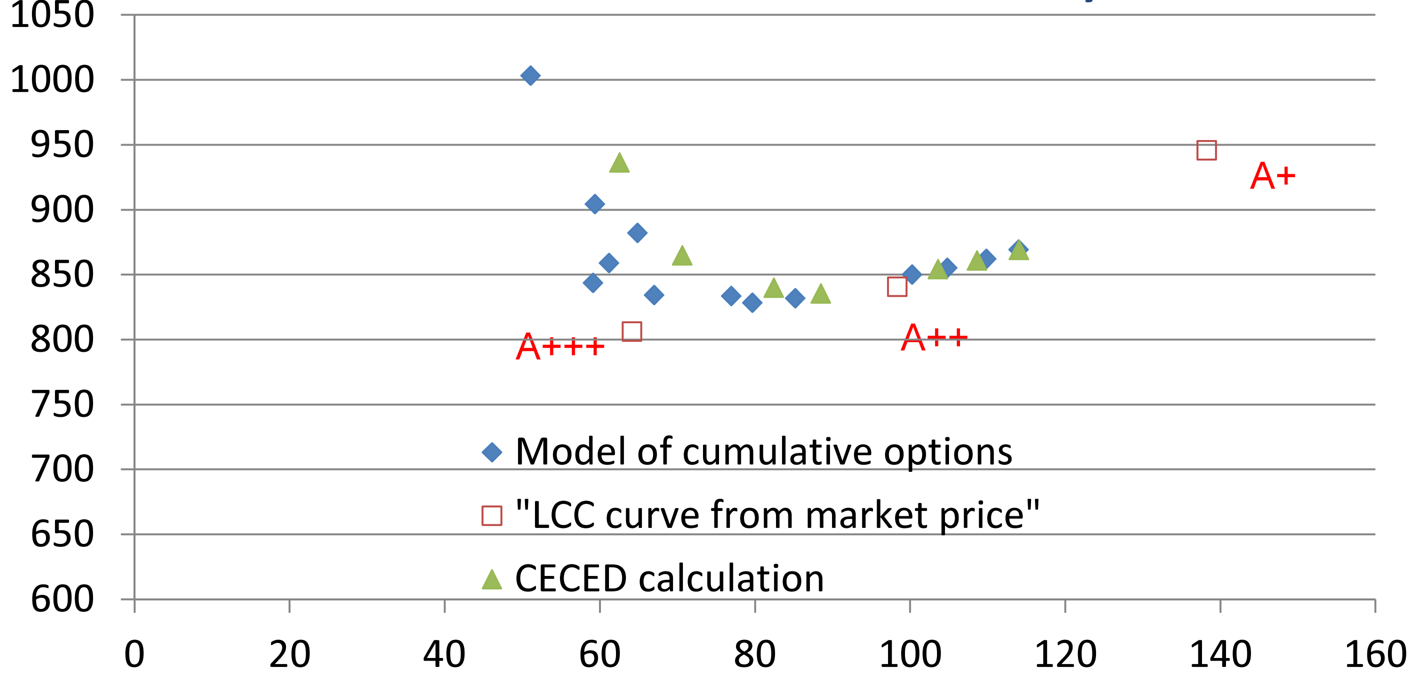
LCC of cumulative options – comparison with market data

- Market data are used to draw comparative LCC curve, using product prices indicated in Task 5
- Illust. Below for COLD1

Energy label class	popu-la-tion	energy	net volume	price per class	price per litre	Price corr.	LCC2
	n=	*kWh/a*	*litre*	*euros*	*eur/litre*	*euros*	
A+	1120	131	240	€ 456	1,90	456,00	€ 849
A++	1228	105	257	€ 514	2,00	480,00	€ 795
A+++	158	71	271	€ 623	2,30	552,00	€ 765

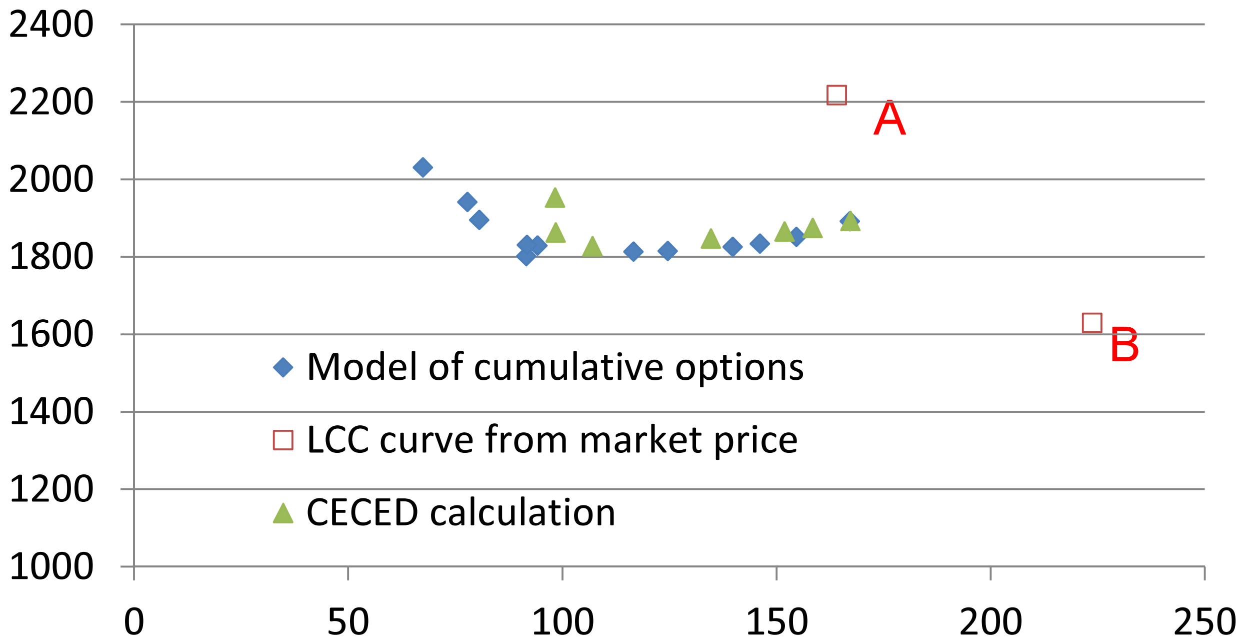
- Note: for COLD2 and COLD8, there are important volume changes for upper classes categories, above resp A+ (COLD2) and A++ (COLD8) cannot be used.

LCC of cumulative options – COLD1, LCC Vs KWh.y



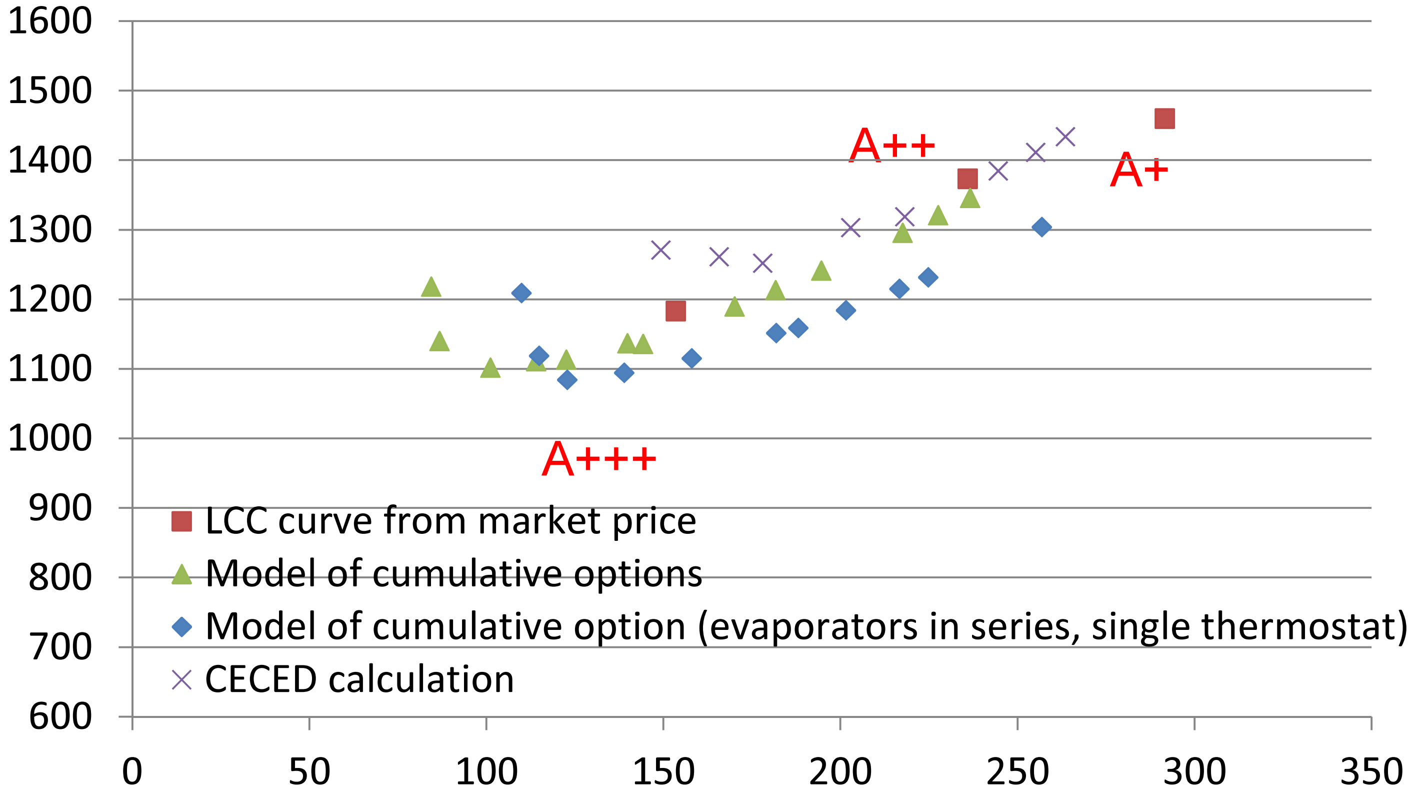
- Model options until LCC: F2 C1 PCM I1 C2
- *CECED calculation: C1 PCM I1*
- F2 calculation to be checked in the report.
- Overshoot on A+++ product price.

LCC of cumulative options – COLD2, LCC Vs KWh.y



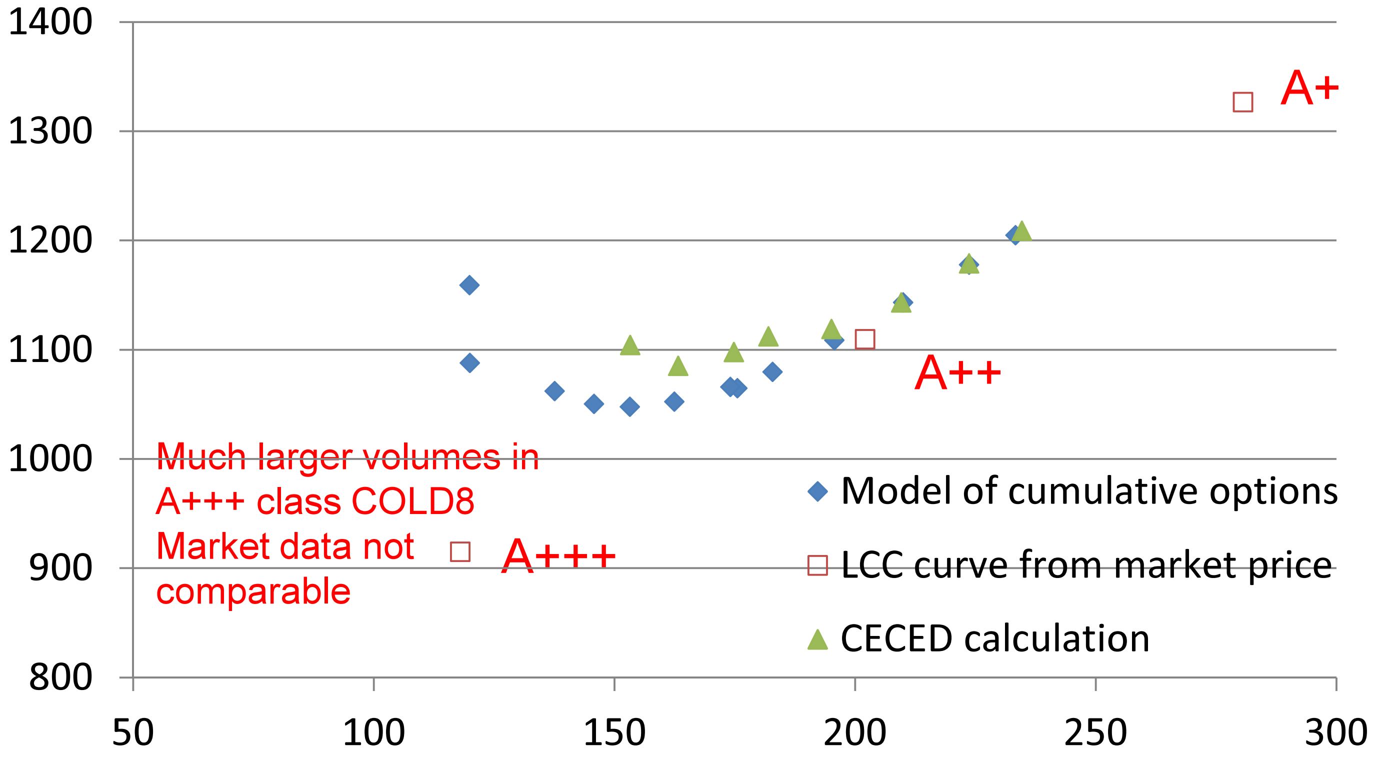
- Model options until LCC: D1 F2 PCM C1 C2 I1
- *CECED calculation:* F2 PCM C1 I1

LCC of cumulative options – COLD7, LCC Vs KWh.y



- Model options until LCC (single thermostat): C1 PCM C2 C3 F2 I1 I2 I3
- Model options until LCC (double thermostat): F2 PCM C1 C2 C3 I1 F1 I2 I4 I3
- *CECED calculation:* F2 PCM C1 C2 I1 - NOTE : starting consumption to be aligned exactly – requires model modification AND adjusted cons. In line with market data average consumption.

LCC of cumulative options – COLD8, LCC Vs KWh.y



- *Model of cumulative option corrected (slight modif / report)*
- Model options until LCC: F2 C1 C2 C3 PCM F1 I1 I2
- *CECED calculation:* F2 C1 C2 C3 PCM I1

LCC of cumulative options –
OVERVIEW & comparison with CECED findings

Table 69. Summary main characteristics of BC, LLCC, BEP and BAT

base case	energy					money				
		BC	LLCC	BEP	BAT		BC	LLCC	BEP	BAT
	kWh/a	114	80	61	51	Price (€)	495	567	658	836
	EEI	36	29	22	19	LCC (€)	869	828	859	1003
COLD1	% gain	ref	30%	46%	69%	SPB (yr)	ref	10.2	15	26.4
	kWh/a	167	92	81	50	Price (€)	1344	1502	1631	2149
	EEI	56	31	27	17	LCC (€)	1892	1802	1895	2314
COLD2	% gain	ref	45%	52%	70%	SPB (yr)	ref	10.5	16.6	34.5
	kWh/a	237	122	na	80	Price (€)	569	708	na	995
	EEI	33	20	na	11	LCC (€)	1345	1109	na	1257
COLD7	% gain	ref	48%	na	66%	SPB (yr)	ref	5.9	na	13.3
	kWh/a	233	151	na	117	Price (€)	439	555	na	805
	EEI	35	23	na	18	LCC (€)	1205	1050	na	1190
COLD8	% gain	ref	35%	na	50%	SPB (yr)	ref	7	na	15.7
	kWh/a	236	147	na	113	Price (€)	356	462	na	607
	EEI	38	24	na	18	LCC (€)	1130	943	na	979
COLD9	% gain	ref	38%	na	52%	SPB (yr)	ref	5.9	na	10.3

BC=Base Case; LLCC=Least Life Cycle Costs point; BEP=Break-Even Point; BAT= Best Available Technology. EEI=Energy Efficiency Index (current regulation); LCC=Life Cycle Costs (euros). SPB=Simple Payback Period (years); na=not available

CECED calculation LLCC

COLD1 - LLCC 22% BEP 38%

COLD2 - LLCC 36% BEP NA

COLD7 - LLCC 37% BEP NA (+ different base case reference used)

COLD8 - LLCC 30% BEP NA

Conclusions

- Present results for engineering analysis close to market values in most cases:
  - Price estimates only slightly higher than market values observed (overcost model > overcost from market data)
  - But little difference on LCC because of high energy price and lifetime
  - Sensitivity analysis to be made at a later stage
- Several corrections to be made in the report
- A technical meeting with CECED and other SH on the modeling part is welcome
- BNAT: to be done together with the technological roadmap

References

1. Matej Visek, Cesare Maria Joppolo, Luca Molinaroli, Andrea Olivani, Advanced sequential dual evaporator domestic refrigerator/freezer: System energy optimization, International Journal of Refrigeration, Volume 43, July 2014, Pages 71-79, ISSN 0140-7007, http://dx.doi.org/10.1016/j.ijrefrig.2014.03.001
2. Yoon, Won Jae; Jung, Hae Won; Chung, Hyun Joon; and Kim, Yongchan, "An Experimental Study on the Performance of a Two- Circuit Cycle with Parallel Evaporators for a Domestic Refrigerator-Freezer" (2010). *International Refrigeration and Air Conditioning Conference. Paper 1042.*
3. *Fantini, M. Innovative techniques to reduce energy consumption of household refrigerators, Politecnico Di Milano, Thesis 2013.*
4. *Hofmanas, I., Reseearches of heat exchange of a wire-and-tube condenser for the increase of refrigerator's efficiency, Summary of Doctoral Dissertation Technological Sciences, Energetics and Power Engineering (06T), 2014, Kaunas*