Energy Performance of Buildings

A quantitative approach to marry calculated Demand and measured Consumption concerning Heating Energy

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1.1 Introduction

- Heat flow through building envelopes and energy expenditure of heat generation are theoretically well understood. Various validated simulation tools are at hand.

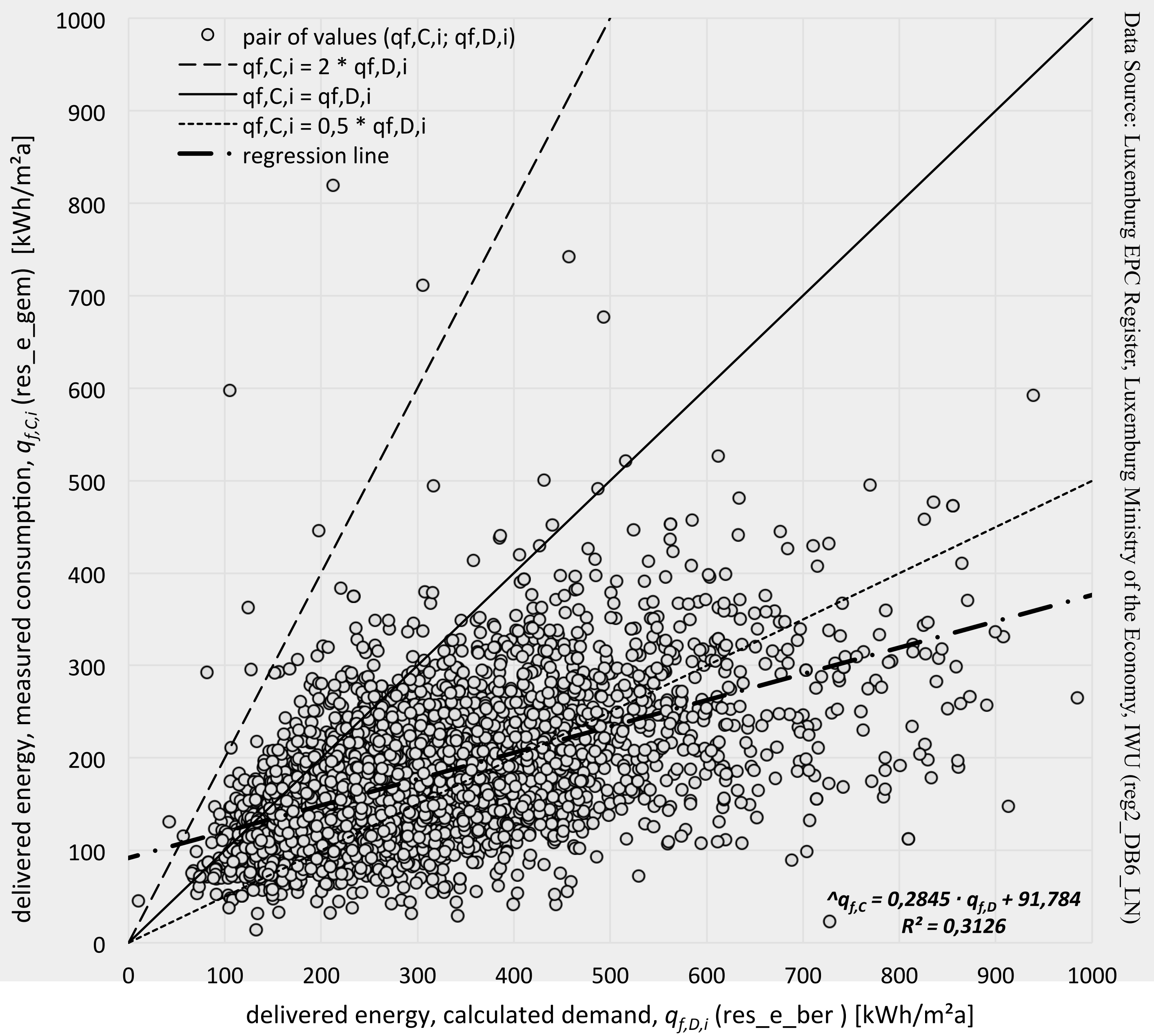
$$q_{f,D} = f(U_i, A_i, e_j, B_k, C_l)$$

- In many cases simplified calculation models are applied, as in Energy Performance Certificates (EPC), assuming standardized specifications of building parameters, user behaviour and climate

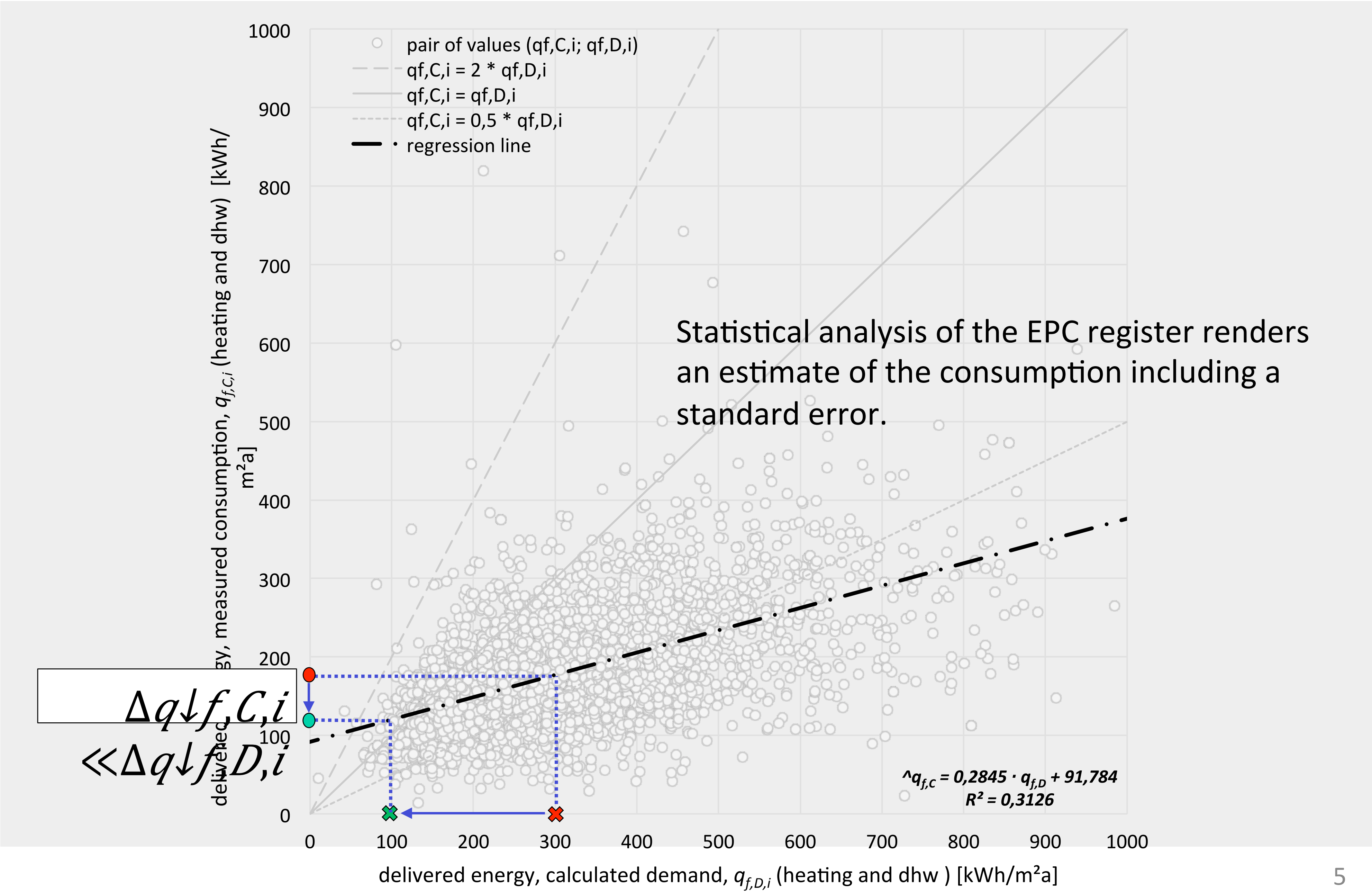
$$q_{f,D}^{EPC} = f^{simplified}(U_i^{std}, A_i^{simplified}, e_j^{std}, B_k^{std}, C_l^{std})$$

- Measured consumption $q_{f,C}$ usually differs from the calculated demand $q_{f,D}$ in a typical manner, in particular when it comes to simplified calculation models of heating Energy.
- These are well-known problems in the empirical sciences. Consumers, though, generally are not aware of these differences.

1.2 Luxemburg EPC Register



1.3 The Trouble is …



2.1 Regression Analysis

Simple Regression Analysis:

- Since the coefficients b_k are unknown, we estimate β_k from the sample
- with the residue
- and the estimate of the standard error

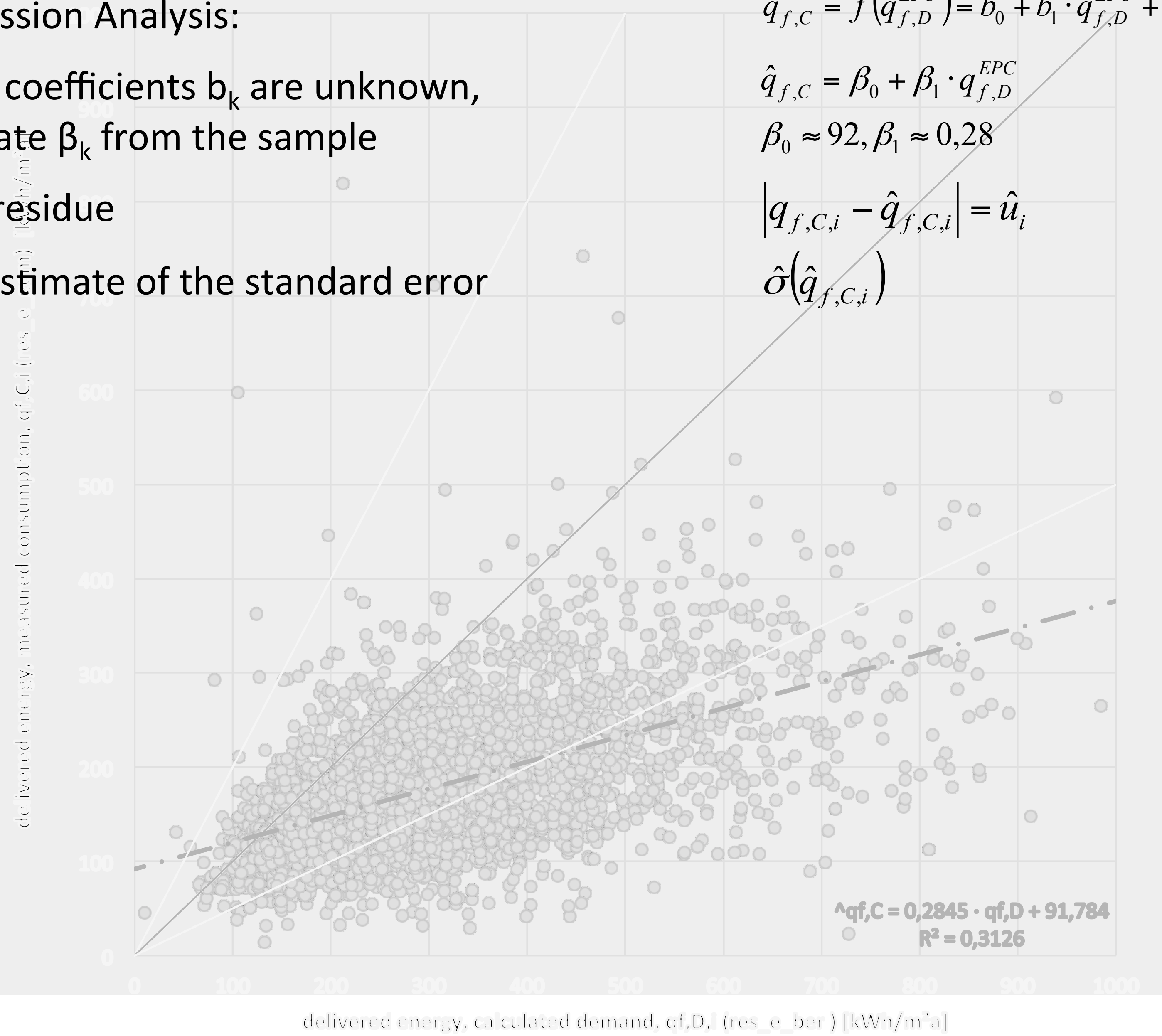
$$q_{f,C} = f\left(q_{f,D}^{EPC}\right) = b_0 + b_1 \cdot q_{f,D}^{EPC} + u$$

$$\hat{q}_{f,C} = \beta_0 + \beta_1 \cdot q_{f,D}^{EPC}$$

$$\beta_0 \approx 92, \beta_1 \approx 0{,}28$$

$$\left| q_{f,C,i} - \hat{q}_{f,C,i} \right| = \hat{u}_i$$

$$\hat{\sigma}\left(\hat{q}_{f,C,i}\right)$$



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- and the estimate of the standard error

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Multiple Regression Analysis:

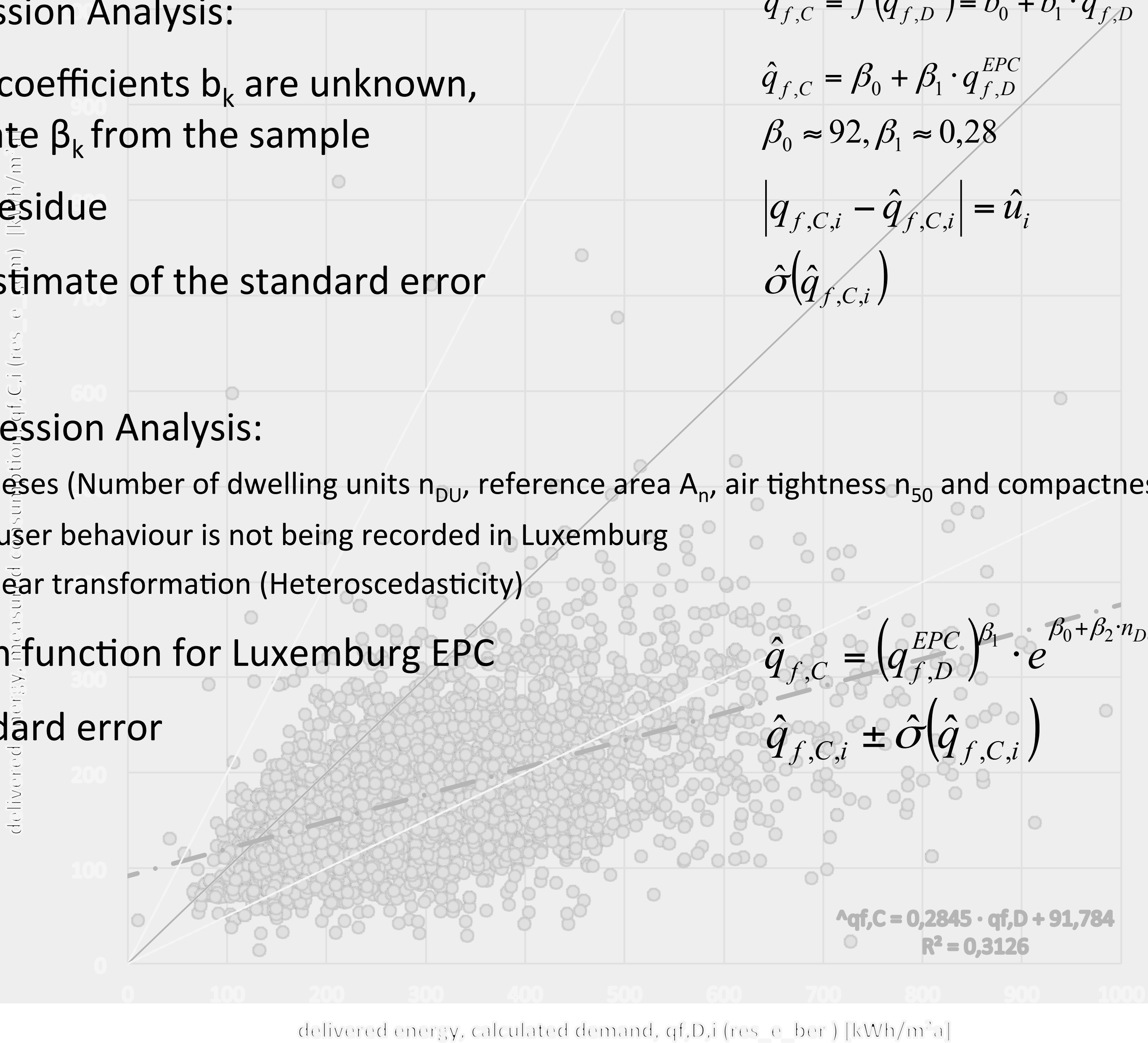
- Hypotheses (Number of dwelling units n_{DU}, reference area A_n, air tightness n_{50} and compactness A/V_e)
- Actual user behaviour is not being recorded in Luxemburg
- Non-linear transformation (Heteroscedasticity)

- Estimation function for Luxemburg EPC

$$\hat{q}_{f,C} = \left(q_{f,D}^{EPC}\right)^{\beta_1} \cdot e^{\beta_0 + \beta_2 \cdot n_{DU} + \beta_3 \cdot A_n + \beta_4 \cdot n_{50} + \beta_5 \cdot A/V_e}$$

- with standard error

$$\hat{q}_{f,C,i} \pm \hat{\sigma}\left(\hat{q}_{f,C,i}\right)$$

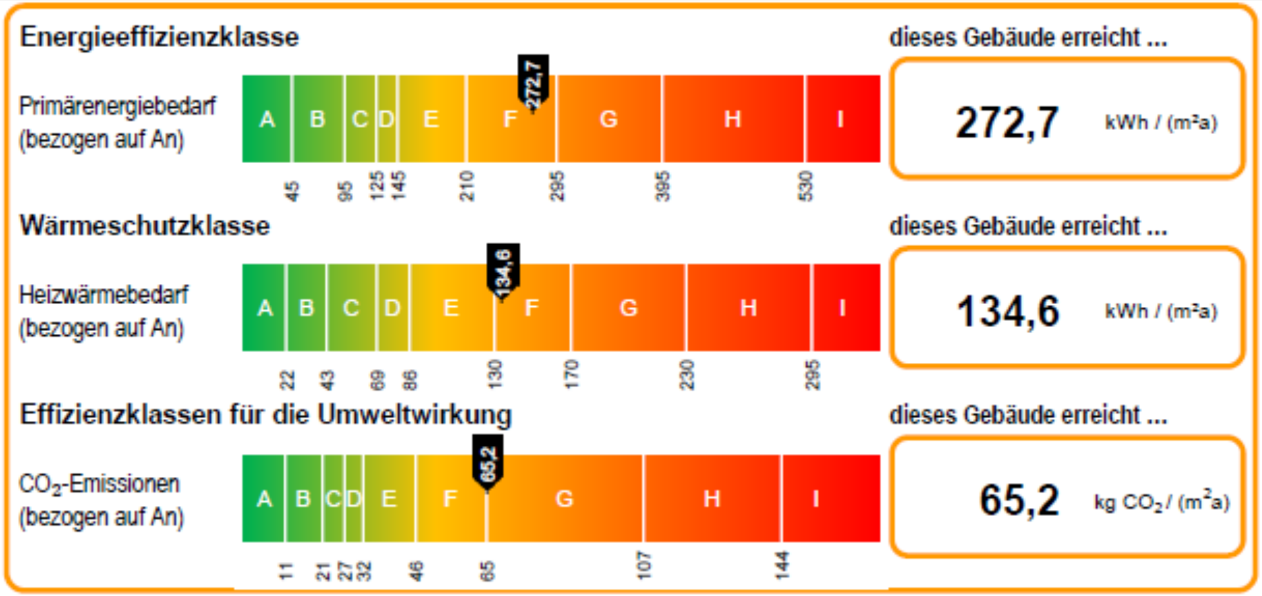


2.2 Luxemburg EPC for Residential Buildings

Primary Energy Demand

Useful Energy Demand

CO_2-Emissions



Verwendung der gemessenen Energieverbräuche

☑ Heizen ☑ Warmwasser ☐ Kochen mit Gas

Schätzung Endenergieverbrauch (berechnet)			*Endenergieverbrauch (gemessen)*		
$Q_{E,B,H,WW}$	149,9 ± 54	kWh / (m² a)	$Q_{E,V,H,WW}$	156,1	kWh / (m² a)

With a probability of 68% the "true" consumption $q_{f,C,i}$ will be in the interval $\hat{q}_{f,C,i} \pm \hat{\sigma}(\hat{q}_{f,C,i})$

Estimated Consumption
$\hat{q}_{f,C,i} \pm \hat{\sigma}(\hat{q}_{f,C,i})$

Measured Consumption
$q_{f,C,i}$
(if available)

New

2.3 User Behaviour and Measurement Error

- In an EPC only standard user behaviour can be regarded, but there is a considerable spread, as we know from various research.

Variable		σ(x)
Room temperature	ϑ_{int} [°C]	±3,3°C
thermally effective window ventilation rate	n [1/h]	±30%
specific internal heat gain	q_{int} [W/m²]	±30%
specific domestic hot water demand	q_{DHW} [kWh/m²a]	±30%

- Applying classical error calculus:

$$\sigma(q_{f,D}) = \sqrt{\left(\frac{\partial q_{f,D}}{\partial \vartheta_{int}} \cdot \sigma(\vartheta_{int})\right)^2 + \left(\frac{\partial q_{f,D}}{\partial n} \cdot \sigma(n)\right)^2 + \left(\frac{\partial q_{f,D}}{\partial q_{int}} \cdot \sigma(q_{int})\right)^2 + \left(\frac{\partial q_{f,D}}{\partial q_{DHW}} \cdot \sigma(q_{DHW})\right)^2 + \ldots}$$

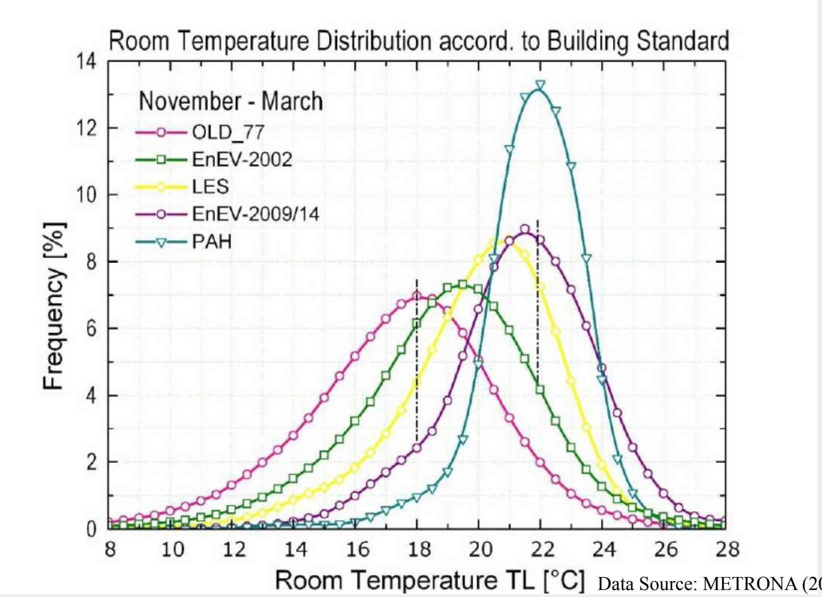
- Renders a relative error in calculated demand of 25% on average

Dwelling	Δq/q	Number of observations
Single-family houses (SFH)	30%	2.788
Small Multi-family houses (sMFH)	22%	938
Multi-family houses (MFH)	10%	681
All houses	25%	4.407

Regression under Measurement Error

Measurement Error in explanatory Variables:

- We assume that $q_{f,D,i}$ was the true demand and further assume $q_{f,D,i}^{EPC}$ to be our best measure of the true demand but it comes with a "measurement" error δ_i: $q_{f,D,i}^{EPC} = q_{f,D,i} + \delta_i$
- Then asymptotically for large samples we get the "attenuation bias" due to errors- in variables $$\lim_p(\beta_1) = b_1 \frac{\sigma^2(q_{f,D,i})}{\sigma^2(q_{f,D,i}) + \sigma^2(\Delta_i)} = b_1\lambda < b_1$$
- The estimator of the slope coefficient, β_1, is always smaller in magnitude than the true value b_1. And this is the tendency we observed in the regression line.
- We need to obtain data, f.i. on user behaviour, from other sources in order to set standards of behavioural parameters B_k as mean values of this observed spread and indicate the uncertainty: $$B_k^{std} = \overline{B}_k \pm \sigma(B_k)$$



Data Source: METRONA (2017)

2.5 Regression under Measurement Error

Measurement Error in dependent Variable:

- To measure the true energy consumption of a building often is quite difficult, since the metering situation is often quite inappropriate.
- Let $q^*_{f,C}$ be the true consumption and $q_{f,C}$ our best measure with a "measurement" error e_0: $q^*_{f,C} = q_{f,C} - e_0$
- We get the estimable model $q^*_{f,C} = b_0 + b_1 \cdot q^{EPC}_{f,D} + u$

$$q_{f,C} = b_0 + b_1 \cdot q^{EPC}_{f,D} + u + e_0$$

- If e_0 and u are uncorrelated, the measurement error in the dependent variable results in a larger error variance: $Var(u + e_0) = \sigma^2_u + \sigma^2_{e_0} > \sigma^2_u$
- The only thing we can do about it, is to measure energy consumption as precise as possible: Metering situation, weather correction, vacancy correction …

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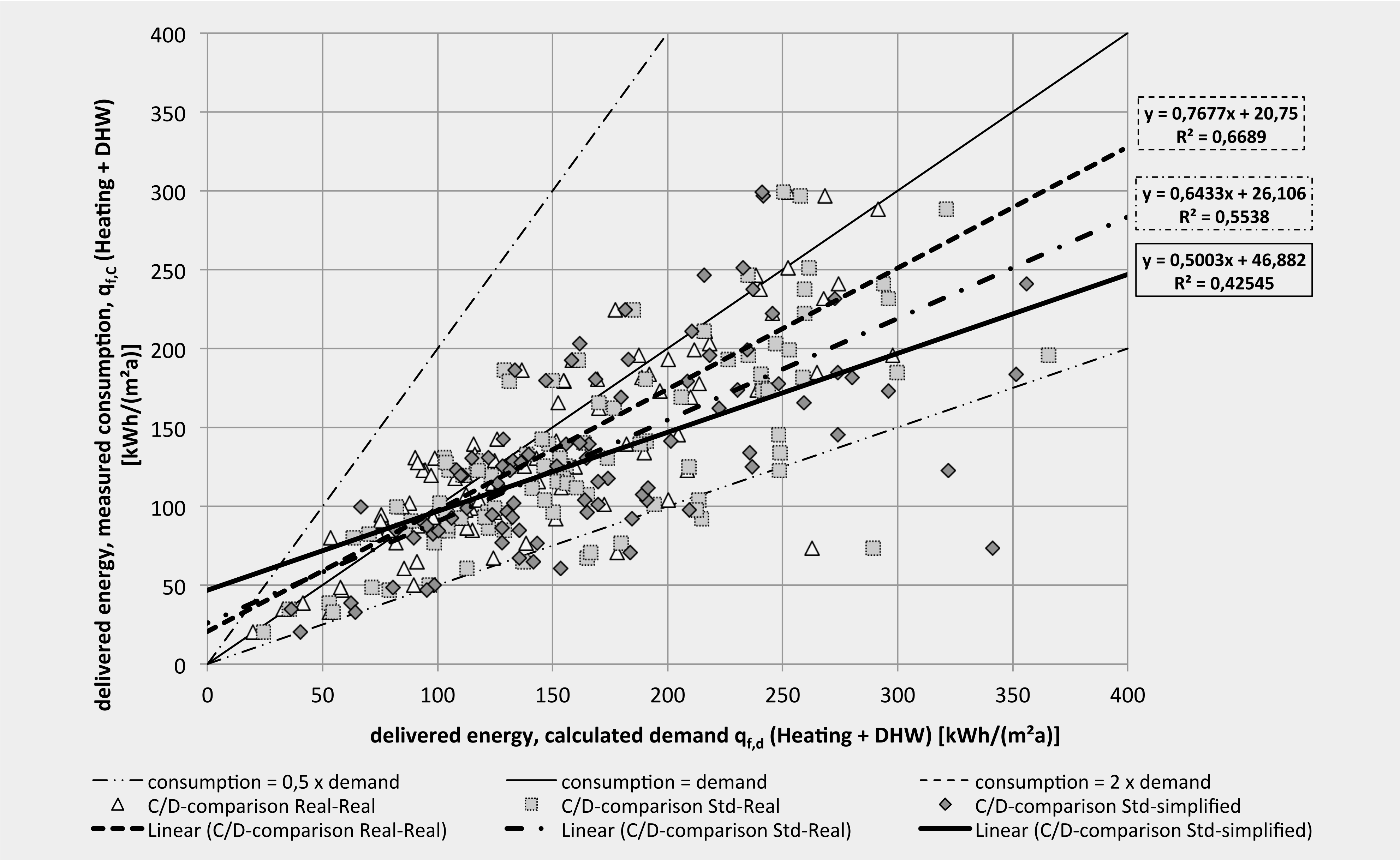
3 Non-residential Buildings in Germany

- The research project “Teilenergiekennwerte von Nichtwohngebäuden” (TEK) within the ENOB research program of the Federal Ministry for Economic Affairs and Energy (BMWi) delivered a database consisting of 92 records of existing non-residential buildings with detailed specific partial energy values.

- Distribution of these 92 non-residential buildings for different classifications

Age band	Number of buildings	Net floor area	Number of buildings	Use	Number of buildings
before 1918	10	up to 1.000 m²	3	Office	23
1919 - 1948	5	1.001 to 5.000 m²	36	Trade	11
1949 - 1977	38	5.001 to 10.000 m²	29	University	19
1978 - 1994	26	10.001 to 30.000 m²	20	Hotel	8
1995 - 2001	7	> 30.000 m²	4	School	15
after 2002	6			Event	16

3.1 Regression Analysis Heating and Hot Water



3.2 Calibration function

- Following our rationale, for the further derivations we focused on the Std-simplified-scheme, which is our preferred candidate for calculations of many buildings in scenarios of a building stock for example. We proposed the multiple regression equation

$$\ln(\hat{q}_{f,C}) = \beta_0 + \beta_1 \cdot f_{winvent,area} + \beta_2 \cdot \Delta q_{\text{int},std-real} + \beta_3 \cdot \Delta t_{use,std-real} + \beta_4 \cdot \Delta\vartheta_{\text{int},std-real} + \beta_5 \cdot \ln(q_{f,D}^{Std-simpl.})$$

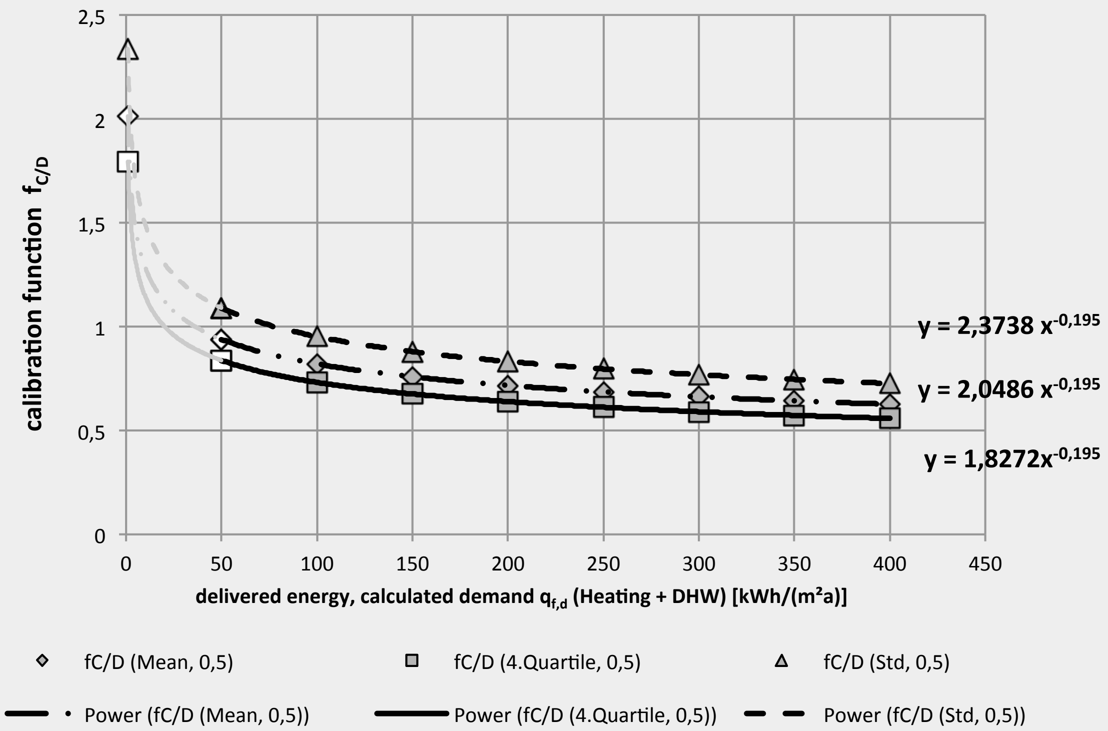
- And derived the estimation function

$$\hat{q}_{f,C} = q_{f,D}^{Std-simpl.\,\beta_5} \cdot e^{\beta_0 + \beta_1 \cdot f_{winvent,area} + \beta_2 \cdot \Delta q_{\text{int},std-real} + \beta_3 \cdot \Delta t_{use,std-real} + \beta_4 \cdot \Delta\vartheta_{\text{int},std-real}}$$
$$= f_{C/D}(q_{f,D}^{Std-simpl.}) \cdot q_{f,D}^{Std-simpl.}$$

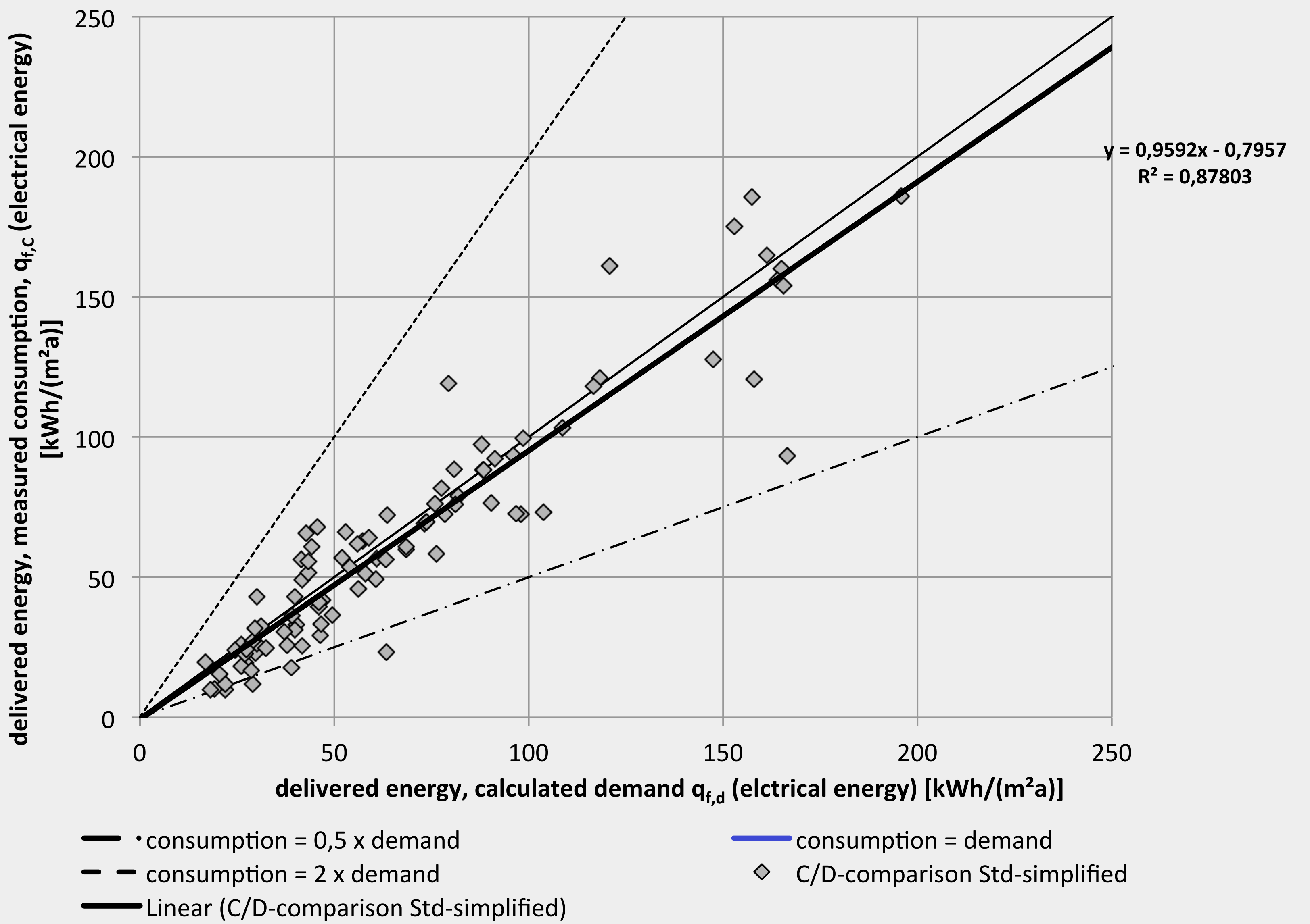
- Rendering the calibration function $f_{C/D}$:

$$f_{C/D} = \frac{\hat{q}_{f,C}}{q_{f,D}^{Std-simpl.}} = \left(q_{f,D}^{Std-simpl.}\right)^{\beta_5 - 1} f_{use}$$

- Calculated savings potentials turn out more reliable



3.3 Electrical Energy



4 Conclusions

- Specific values of calculated energy demand for heating and domestic hot water deviate from measurements f.i. in energy bills, even in realistic calculation models, but considerably in simplified models.
- Simplified calculation models are used for typology based calculations in buildings stocks or as in EPCs made to inform about the energy-related quality of buildings and to certify compliance with Energy Performance Ordinances irrespective of user behaviour and climate parameters.
- Statistical analysis can provide calibration to real consumption and realistic estimates of the uncertainties in the calculations, as in the new EPC in Luxemburg or in the calculation of energy savings.
- The distribution of user behaviour parameters has to be quantitatively analysed and an EPC database including assured consumption values should be established.
- For buildings stocks' analyses simplified calculation models with well-defined standard specifications including uncertainties and calibration functions are appropriate method to predict the future energy consumption of the building sector in scenario calculations.
- We consider the quantification of uncertainties of the calculation models as necessary in order to use their results as a sound base for decision making in the political arena.