Impact of measurement uncertainty on building modeling and retrofitting decisions - Appendix

1 Appendix A. Heating system efficiency and sizing

For heat pumps, we consider seasonal performance factors for space heating (SPF_h) and DHW (SPF_{DHW}).

1.1 Appendix A.1. Air-to-water heat pumps

The bin-method was used from the Swiss standard SIA 384/3 (Swiss Society of Engineers and Architects (SIA), 2013) for the determination of the seasonal performance factors of heat pumps, as seen in Eq. 1.

$$COP(t) = a_0 + a_1 \cdot T_{source}(t) + a_2 \cdot T_{supply}(t) + a_3 \cdot T_{source}(t) \cdot T_{supply}(t) + a_4 \cdot T_{source}(t)^2 + a_5 \cdot T_{supply}(t)^2 \quad \textbf{Eq. 1}$$

For air-to-water heat pumps, the external temperature $T_e(t)$ is used as $T_{source}(t)$ in Eq. 1.

The hourly electricity demand for space heating is calculated by dividing the hourly space heating load $\Phi_H(t)$ by the coefficient of performance at the same time $COP(t)$ and multiplying by one hour for the conversion from power to energy as seen in Eq. 2.

$$E_h(t) = \frac{\Phi_\mathrm{h}(t) \cdot 1h}{COP(t)} \quad \textbf{Eq. 2}$$

Then the seasonal coefficient of performance follows from Eq. 3.

$$SCOP_h = \frac{\sum_{t=1}^{8760} \Phi_\mathrm{h}(t) \cdot 1h}{\sum_{t=1}^{8760} \mathrm{E_h}(t)} \quad \textbf{Eq. 3}$$

In Eq. 3, $\Phi_H(t)$ is the hourly space heating load, and $E_h(t)$ is the hourly electricity demand for space heating.

The electricity demand for the circulation pump $E_{add,h}$ is calculated by multiplying the time of operation of the pump with the power of the circulation pump as seen in Eq. 4.

$$E_{add,h} = t_{pump,h} \cdot P_{pump} \qquad \textbf{Eq. 4}$$

The seasonal performance factor for space heating SPF_h is then calculated with Eq. 5.

$$SPF_h = \frac{\eta_{hp}}{\frac{1}{SCOP_h} + \frac{E_{add,h}}{Q_h}} \qquad \textbf{Eq. 5}$$

In Eq. 5, η_{hp} is the efficiency of the heat pump considering losses due to on-off cycling and Q_h is the yearly space heating demand of the building.

Due to the assumption of constant DHW supply temperature (T_{DWH}) and demand, the seasonal coefficient of performance for DHW can be calculated using Eq. 6.

$$SCOP_{DHW}(t) = a_0 + a_1 \cdot T_{source,avg}(t) + a_2 \cdot T_{DHW}(t) + a_3 \cdot T_{source,avg}(t) \cdot T_{DHW}(t) + a_4 \cdot T_{source,avg}(t)^2 + a_5 \cdot T_{DHW}(t)^2 \qquad \textbf{Eq. 6}$$

In Eq. 6, $T_{source,avg}$ is the yearly average outdoor air temperature that serves for air-to-water heat pumps. The calculation of $T_{source,avg}$ for geothermal heat pumps is available in Appendix A.

Auxiliary energy for DHW generation includes the energy for the circulation pump P_{pump}, and for the weekly heating of the DHW storage to 60°C for thermal disinfection as seen in Eq. 7.

$$E_{add,DHW} = t_{pump,DHW} \cdot P_{pump} + 52 \cdot V_{DHW,storage} \cdot (60°C - T_{DHW}) \cdot c_{p,water} \cdot \rho_{water} \qquad \textbf{Eq. 7}$$

In Eq. 7, V_{DHW} storage is the volume of the DHW storage tank.

The seasonal performance factor for DHW is calculated in Eq. 8.

$$SPF_{DHW} = \frac{\eta_{hp}}{\frac{1}{SCOP_{DHW}} + \frac{E_{add,DHW}}{Q_{dhw}}} \qquad \textbf{Eq. 8}$$

In Eq. 8, η_{hp} considers losses of the buffer storage. The final energy for space heating and domestic hot water ($FED_{h\&DHW}$) is calculated as in Eq. 9.

$$FED_{h\&DHW} = \frac{Q_h}{SPF_h} + \frac{\frac{Q_{DHW}}{\eta_{DHW}}}{SPF_{DHW}} \quad \textbf{Eq. 9}$$

1.2 Appendix A.2. Ground source heat pump

For geothermal heat pumps, the $T_{source,avg}$ in Eq. 10 is the source temperature of the geothermal probe T_{source}. It is assumed to be constant and calculated according to (Swiss Society of Engineers and Architects (SIA), 2013; Huber and Stalder, 2020):

$$T_{source} = 10°C - \left(0.005\frac{°Cm}{W} + \frac{t_{op}}{100h} \cdot 0.006\frac{°Cm}{W}\right) \cdot \Phi_{h,max} \cdot \frac{\frac{1000W}{kW}}{L_{probe}} \cdot \frac{COP_{B0/W35}-1}{COP_{B0/W35}} \quad \textbf{Eq. 10}$$

where $COP_{B0/W35}$ is the COP at $T_{source} = 0°C$ and $T_{supply} = 35°C$. t_{op} [h] is the total operating time of the heat and calculated as

$$t_{op} = \frac{Q_h + Q_{DHW}}{\Phi_{h,max}} \quad \textbf{Eq. 11}$$

2 Appendix B. Design parameters

Table 2.1: List of design parameters chosen for the building energy assessment, cost assessment, and environmental assessment

Variable	Value	Source
$T_{i,design}$	20 °C	SIA 380/1 (Swiss Society of Engineers and Architects (SIA), 2016)
$T_{e,design}$	-9 °C	SIA 2028 (Swiss Society of Engineers and Architects (SIA), 2010)
T_{limit}	15 °C	Assumption based on oil boiler setting in case study building
ΔT	8 °C	Assumption
$V_{DHW,storage}$	0.3 m3/d	DHW storage in case study building
P_{pump}	50 W	Manual of pump in case study building
$t_{pump,h}$	2300 h	Handbook (Swiss Federal Office of Energy, 2019)
$t_{pump,DHW}$	400 h	Handbook (Swiss Federal Office of Energy, 2019)
$\eta_{h,geo}$	SPF_h, SPF_{DHW}	Appendix A
$\eta_{h,air}$	SPF_h, SPF_{DHW}	Appendix A
$\eta_{h,district}$	0.97	SIA 380/1 (Swiss Society of Engineers and Architects (SIA), 2016)
$\eta_{h, wood}$	0.75	SIA 380/1 (Swiss Society of Engineers and Architects (SIA), 2016)
η_{hp}	0.96	SIA 380/1 (Swiss Society of Engineers and Architects (SIA), 2016)
η_{DHW}	0.8	SIA 380/1 (Swiss Society of Engineers and Architects (SIA), 2016)
P_{Wood}	0.08 CHF/kWh	IEA EBC Annex 56 (Ott et al., 2017)
$P_{District\ heat}$	0.09 CHF/kWh	IEA EBC Annex 56 (Ott et al., 2017)
$P_{Electricity}$	0.21 CHF/kWh	IEA EBC Annex 56 (Ott et al., 2017)
$CF_{GHG,Wood}$	0.027 kg-CO2/kWh	KBOB 2016 (Bächtold et al., 2016)
$CF_{GHG,District}$	0.108 kg-CO2/kWh	KBOB 2016 (Bächtold et al., 2016)
$CF_{GHG,Electricity}$	0.102 kg-CO2/kWh	KBOB 2016 (Bächtold et al., 2016)
IC_{Wood}	97 CHF/kW	Quotation (Sigrist et al., 2019)
$IC_{District}$	128 CHF/kW	Quotation (Sigrist et al., 2019)
IC_{air}	648 CHF/kW	Quotation (Sigrist et al., 2019)
IC_{geo}	2122 CHF/kW	Quotation (Sigrist et al., 2019)
r_{ec}	0%	Assumption
r	0%	Assumption
τ	30 years	Assumption

3 References

Almeida, M., and Ferreira, M. (2018). Ten questions concerning cost-effective energy and carbon emissions optimization in building renovation. *Building and Environment* 143, 15–23. doi:10.1016/j.buildenv.2018.06.036.

Alzetto, F., Pandraud, G., Fitton, R., Heusler, I., and Sinnesbichler, H. (2018). QUB: A fast dynamic method for in-situ measurement of the whole building heat loss. *Energy and Buildings* 174, 124–133. doi:10.1016/j.enbuild.2018.06.002.

Bächtold, H., Egli, N., Frei, K., Friedli, R., Frischknecht, R., and Gugerli, H. (2016). Empfehlung nachhaltiges Bauen - Ökobilanzen im Baubereich. *KBOB; eco-bau; IPB, Eds. KBOB: Switzerland*.

Bau- und Wohnungswesen 2018 (2020). Neuchâtel: Bundesamt für Statistik (BFS) Available at: https://www.bfs.admin.ch/hub/api/dam/assets/12507412/bibtex.

Bauwens, G., and Roels, S. (2014). Co-heating test: A state-of-the-art. *Energy and Buildings* 82, 163–172. doi:10.1016/j.enbuild.2014.04.039.

Cozza, S., Chambers, J., Deb, C., Scartezzini, J.-L., Schlüter, A., and Patel, M. K. (2020). Do energy performance certificates allow reliable predictions of actual energy consumption and savings? Learning from the Swiss national database. *Energy and Buildings* 224, 110235. doi:10.1016/j.enbuild.2020.110235.

Deb, C., Frei, M., Hofer, J., and Schlueter, A. (2019). Automated load disaggregation for residences with electrical resistance heating. *Energy and Buildings* 182, 61–74. doi:10.1016/j.enbuild.2018.10.011.

Dimitriou, V. (2016). Lumped parameter thermal modelling for UK domestic buildings based on measured operational data. Available at: https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/23239 [Accessed March 11, 2017].

EU Commission (2012). Commission delegated regulation (EU) no 244/2012 of 16 january 2012 supplementing directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of buildings. *Official Journal of the European Union* 55, 18–36.

Frei, M., Deb, C., Nagy, Z., Hischier, I., and Schlueter, A. (2021). Building Energy Performance Assessment Using an Easily Deployable Sensor Kit: Process, Risks, and Lessons Learned. *Front. Built Environ.* 6. doi:10.3389/fbuil.2020.609877.

Frei, M., Deb, C., Stadler, R., Nagy, Z., and Schlueter, A. (2020). Wireless sensor network for estimating building performance. *Automation in Construction* 111, 103043. doi:10.1016/j.autcon.2019.103043.

Galimshina, A., Moustapha, M., Hollberg, A., Padey, P., Lasvaux, S., Sudret, B., et al. (2020). Statistical method to identify robust building renovation choices for environmental and economic performance. *Building and Environment* 183, 107143. doi:10.1016/j.buildenv.2020.107143.

Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme (2019). *2019 Global Status Report for Buildings and Construction: Towards a zero-emission, efficient and resilient buildings and construction sector.* Available at: https://webstore.iea.org/download/direct/2930?fileName=2019_Global_Status_Report_for_Buildings_and_Construction.pdf.

Hall, M. (2020). Normierung des GEAK®. Konferenz Kantonaler Energiedirektoren Available at: https://www.endk.ch/de/ablage/grundhaltung-der-endk/20200402_Normierung_GEAK_EnDK_D.pdf.

Heo, Y., Augenbroe, G., Graziano, D., Muehleisen, R. T., and Guzowski, L. (2015). Scalable methodology for large scale building energy improvement: Relevance of calibration in model-based retrofit analysis. *Building and Environment* 87, 342–350. doi:10.1016/j.buildenv.2014.12.016.

Heo, Y., Choudhary, R., and Augenbroe, G. A. (2012). Calibration of building energy models for retrofit analysis under uncertainty. *Energy and Buildings* 47, 550–560. doi:10.1016/j.enbuild.2011.12.029.

Huber, A., and Stalder, M. (2020). Rechenmethode WPesti - Handbuch.

International Organization for Standardization (2006). ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework. Available at: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html [Accessed November 5, 2020].

International Organization for Standardization (2008). ISO 13790:2008 - Energy performance of buildings - Calculation of energy use for space heating and cooling. International Organization for Standardization Available at: http://www.iso.org/iso/catalogue_detail.htm%3Fcsnumber=41974 [Accessed July 25, 2016].

Kemmler, A., and Spillmann, T. (2020). Analyse des schweizerischen Energieverbrauchs 2000–2019 nach Verwendungszwecken. Bern, Switzerland: Swiss Federal Office of Energy Available at: https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/energieverbrauch-nach-verwendungszweck.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTAyNjA=.html.

Khoury, J., Hollmuller, P., and Lachal, B. M. (2016). Energy performance gap in building retrofit: characterization and effect on the energy saving potential. in.

Lee, S. H., Hong, T., Piette, M. A., and Taylor-Lange, S. C. (2015). Energy retrofit analysis toolkits for commercial buildings: A review. *Energy* 89, 1087–1100.

Ma, Z., Cooper, P., Daly, D., and Ledo, L. (2012). Existing building retrofits: Methodology and state-of-the-art. *Energy and Buildings* 55, 889–902. doi:10.1016/j.enbuild.2012.08.018.

Ott, W., Bolliger, R., Ritter, V., Citherlet, S., Lasvaux, S., Favre, D., et al. (2017). *Methodology for cost-effective energy and carbon emissions optimization in building renovation (Annex 56).*

Universidade do Minho Available at: http://repositorium.sdum.uminho.pt/ [Accessed May 25, 2021].

Papafragkou, A., Ghosh, S., James, P. A. B., Rogers, A., and Bahaj, A. S. (2014). A simple, scalable and low-cost method to generate thermal diagnostics of a domestic building. *Applied Energy* 134, 519–530. doi:http://dx.doi.org/10.1016/j.apenergy.2014.08.045.

Programme, U. N. E., and Agency, I. E. (2018). *2018 Global Status Report - Towards a zero-emission, efficient and resilient buildings and construction sector*. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/27140/Global_Status_2018.pdf.

Reid, E. (1984). *Understanding Buildings: A Multidisciplinary Approach*. MIT Press.

Rysanek, A. M., and Choudhary, R. (2013). Optimum building energy retrofits under technical and economic uncertainty. *Energy and Buildings* 57, 324–337. doi:10.1016/j.enbuild.2012.10.027.

Sigrist, D., Deb, C., Frei, M., and Schlueter, A. (2019). Cost-optimal retrofit analysis for residential buildings. in *Journal of Physics: Conference Series*, 012030. doi:10.1088/1742-6596/1343/1/012030.

Sigrist, D., Deb, C., and Schlueter, A. (2020). A calibrated RC model for dataxdriven retrofit analysis of a residential building. in *eSIM 2020-2021 Vancouver*.

Sunikka-Blank, M., and Galvin, R. (2012). Introducing the prebound effect: the gap between performance and actual energy consumption. *Building Research & Information* 40, 260–273.

Swiss Federal Office of Energy (2019). Leistungsgarantie Haustechnik.

Swiss Society of Engineers and Architects (SIA) (2010). *SIA 2028:2010 Klimadaten für Bauphysik, Energie- und Gebäudetechnik*. SIA.

Swiss Society of Engineers and Architects (SIA) (2013). *SIA 384/3:2013 Heizungsanlagen in Gebäuden - Energiebedarf*. SIA.

Swiss Society of Engineers and Architects (SIA) (2015). *SIA 2024:2015 Raumnutzungsdaten für die Energie- und Gebäudetechnik*. SIA.

Swiss Society of Engineers and Architects (SIA), S. S. of E. {and} (2016). *SIA 380/1:2016 Heizwärmebedarf*. SIA.

Tadeu, S., Rodrigues, C., Tadeu, A., Freire, F., and Simões, N. (2015). Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions. *Journal of Building Engineering* 4, 167–176. doi:10.1016/j.jobe.2015.09.009.

Tian, W., Heo, Y., de Wilde, P., Li, Z., Yan, D., Park, C. S., et al. (2018). A review of uncertainty analysis in building energy assessment. *Renewable Sustainable Energy Rev.* 93, 285–301.