Comparing extracting and recirculating residential kitchen range hoods for the use in high energy efficient housing

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ABSTRACT

Residential cooking can be a significant indoor source of odour, pollutants and particulate matter. Conventionally, range hoods expel the air into the ambient. A number of studies have investigated their contaminant capture performance. However, for highly energy efficient houses the installation of extracting range hoods can pose certain challenges, e.g. high ventilation losses, additional thermal bridges and potential air leakage sites. Therefore, the use of recirculation range hoods has become standard for highly energy efficient housing with mechanical ventilation with heat recovery in Central Europe.
Open questions remain regarding their capture and filtration efficiency as a function of filter age, especially for particles and odours. But also, the actual energy savings potential when using recirculating instead of extracting devices in a highly energy efficient housing had not been documented yet. This paper addresses these questions with a literature review and an energetic comparison.
The review identified a good number of studies which have investigated the capture performance of extracting range hoods with a focus on pollutants resulting from gas combustion and/or the cooking generated particles. These studies show that capture efficiency, in particular for front burner use, can vary drastically for different designs and that particle capture does not necessarily match capture efficiency for gaseous contaminants. No scientific study investigating the performance of recirculating range hoods was found. Tests for consumer magazines as well as surveys indicate notably lower performance compared to extracting hoods. In summary one can say that performance tests are urgently needed to quantify the capture and filter efficiency for particles and (odorous) organic compounds as a function of filter age.

KEYWORDS

Kitchen ventilation, Extracting range hood, Recirculating range hood, Capture Efficiency

1 INTRODUCTION

Residential cooking can be a significant indoor source of odour, pollutants and particulate matter (PM). Range hoods are intended to remove the majority cooking generated contaminants directly at the source before mixing with the rest of the air in the room. Conventionally, range hoods expel the air into the ambient. Usually these range hoods run at a volume flow of around 200-500 m³/h (50-150 l/s) and this contributes to additional home heating and cooling load. At higher air flows, there is the possibility that the resulting increase in envelope pressures may reduce the air flow through exhaust air system in other rooms (e.g., bathrooms and toilets) (Huber & Pluess, 2004). The required airflow openings penetrating the building envelope create additional thermal bridges and potential air leakage sites. For low-energy housing, such as Passive Houses (PH), these issues are considered problematic. Therefore, the use of recirculation range hoods has become standard for highly energy efficient housing with mechanical ventilation with heat recovery (MVHR) in Central Europe. They do not expel the extract air to the ambient, but release the filtered air back into the kitchen. The filtration typically consists of a grease removal screen followed by an activated carbon (AC) filter. Open questions remain regarding their capture and filtration efficiency as a function of filter age, especially for PM and odours. Even if one assumes a sufficiently good contaminant removal performance, the question arises on how much energy can actually be saved with a recirculating compared to an extracting range hood? A study on the energy impacts of using extracting range hoods in US homes concludes that reducing the required airflow to obtain adequate pollutant capture would have the largest energy savings potential (Logue & Singer, 2014).

This paper addresses these questions with a literature review on capture efficiency of extracting and recirculating range hoods, looking at metrics, available standards and existing studies where capture performance has been measured. Finally, both range hood concepts are compared in terms of their energy use.

2 PERFORMANCE TESTING OF RESIDENTIAL KITCHEN RANGE HOODS

How effectively a kitchen range hood removes the pollutants depends on a number of variables. Besides obvious parameters like flow rate, hood design and position, there are less obvious influencing variable like the air currents in the room (Rong Fung Huang et al. 2015; Rong Fung Huang et al. 2010; Kim et al. 2017) and the cooking-generated thermal plume, which in turn depends on the heat input, the type of cooking, etc. (Walker et al. 2017). The removal of contaminants is quantified by the capture efficiency (CE), i.e., the fraction of the cooking pollutants that are removed and not allowed to mix with the air in the kitchen (and the rest of the home). CE has been used in previous studies and the new ASTM (ASTM 2017) test method based on the exhausting the pollutants to outside, but could also be used for recirculating hoods to represent the fraction of pollutants removed by the hood before the air returns to the kitchen.

2.1 Definitions of Capture Efficiency

The general definition of CE is the ratio of mass of contaminant removed to the mass of contaminant produced at the source. Both can be challenging to measure directly, so the following simple equation is widely used because its simplicity and the fact that it involves input values that are easy to measure (Wolbrink et al., 1992).

$$\varepsilon = 1 - \frac{c_R - c_A}{c_{RH} - c_A} = \frac{c_{RH} - c_R}{c_{RH} - c_A} \quad (1)$$

Here c_R, c_{RH} and c_A are the concentrations in the room, in the range hood extract and in ambient. For recirculating range hoods this derivation for CE is not applicable. A corresponding model for recirculating hoods is proposed in Figure 1(b). It has three zones and splits the total contaminant removal efficiency ε_{Total} into the “fluid-dynamic” CE (ε_{CE}) and the filter removal efficiency (ε_{Filter}). To solve the corresponding set of mass balance equations either S or $\dot{m}_{Fil}$ needs to be known. Depending on the pollutants, these could be hard to measure, e.g. the particle source term. Instead a method based on measuring the room contaminant concentration with and without the range hood in operation can be used:

$$\varepsilon = 1 - \frac{\int (c_R - c_A)dt}{\int (c_{R\_noRH} - c_{A\_noRH})dt} \quad (2)$$

The subscript “*noRH”* stands for “no range hood”, indicating the concentrations measured with the range hood not being operated. This method can also be applied to non-continuous sources, like real cooking. It has also been applied for determining the CE for PM of extracting range hoods (Lunden, Delp, & Singer, 2015), since measuring the PM concentration of the extracted cooking fumes is problematic. Here the challenge is providing identical experimental conditions, including the source emission rate, for the set of runs needed to determine the CE. For steady state emission sources and non-contaminated ambient air, Eqn. 2 simplifies to Eqn. 3. This approach is also used within ISO 61591. Note all presented definitions apply the concept of “first pass” or “direct” CE.

$$\varepsilon = 1 - \frac{c_R}{c_{R\_noRH}}. \quad (3)$$

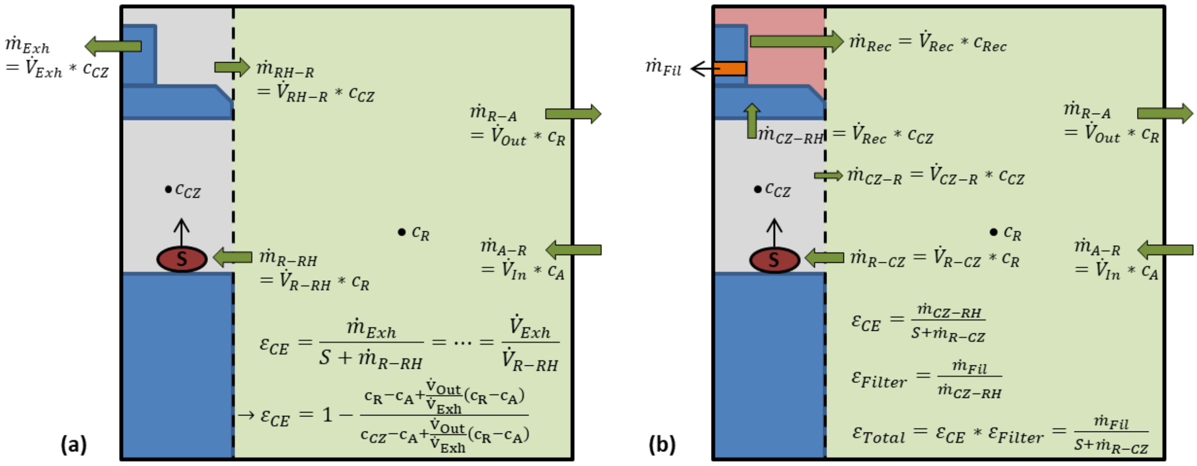

Figure 1: Schematic showing the conceptual models for deriving the capture efficiency ε_{CE} (a) for extracting range hoods and (b) for recirculating range hoods. See text for more details.

2.2 Standards covering residential range hood performance

Residential ventilation standards have usually no specific requirement on the kitchen range hood. However they usually have general kitchen ventilation requirements, e.g. the ASHRAE Standard 62.2 requires either an intermittent ventilation rate of 50 L/s (100 cfm) or a continuous air exchange rate of 5 Air Changes per Hour (ACH) for the kitchen. The Austrian standard applicable to residential mechanical ventilation ÖNORM H 6038 (2004) requires a minimal extract air flow of 30 m^3/h (8 L/s) for the kitchen.

Whereas there a number of standards addressing commercial kitchen range hoods (ASHRAE154, ASTM F1704-09, VDI 2052, EN16282-2 through -9), there are only a few standards addressing the performance of residential kitchen range hoods. The guideline from the Home Ventilating Institute (**HVI**) requires a minimal air flow of 40 cfm/foot of cooktop length , so 100 cfm (170 m3/h = 47 l/s) for a typical US range width of 30 inches (76 cm). The **Energy star** label addresses energy efficiency by requiring the fan efficacy to be ≥2.8 cfm/W (0.21 Wh/m3). It also limits the maximal air flow to 500 cfm and the sound to ≤2 sone.

ISO 61591 covers methods to measure grease and odour removal performance. It can be applied to either extracting or recirculating range hoods. The odour extraction test is to be done in a symmetrically arranged test room with a volume of 22 m^3+/-2 m^3 (3.5x2.5x2.5m). A mix of 12 g methyl-ethyl ketone (MEK) and 300 g distilled water is dripped into a pan having a temperature of 170°C. The dripping rate should be adjusted so that this evaporation process takes 30 minutes. After that, the air in the test room is mixed with a room ventilator and the MEK concentration is measured in a certain position in the room at four different heights. The odour reduction factor O_f is determined as the relative difference of concentration C with and without use of range hood:

$$O_f = \frac{C_{without} - C_{with}}{C_{without}}. \quad (4)$$

Extracting range hoods are turned off directly after the evaporation process. The test room is otherwise not ventilated throughout the experiment. Recirculating range hoods are operated continuously even after the source has been removed. Besides O_f, the odour dispersion time is determined as the time it takes for the MEK concentration to reach 15% of its peak value without range hood use. Odour extraction filters are to be conditioned at 50°C for 16 hours prior to the test. For the grease absorption test, 48 g of corn oil and 69 g of water are dripped into a pan in 30 minutes, the pan having a temperature of 250°C. The grease absorption factor is determined as the ratio of mass of grease retained in the grease filter and total mass of grease removed by ventilation equipment, i.e. in the range hood (including filter and -airways) and in a filter (placed at the hood outlet). It is interesting to note that **EN13141-3** which covers residential cooking hoods without fan requires the use of a “disturbing element” in front of the range when performing the odour extraction test. This disturbing element is to be moved periodically left and right to simulate air movements produced by a person. Otherwise the test method in EN13141-3 is very similar to ISO 61591.

A new ASTM standard (ASTM, 2017) has been developed to measure CE using racer gas techniques for wall mount hoods. Further information on the development of this test method can be found in (I S Walker, Stratton, Delp, & Sherman, 2016). A standardized test method for island and downdraft range hoods is also being developed (Iain S Walker et al., 2017). The principle of both test methods is to determine the CE using tracer gas (e.g. CO_2) emitted through specifically designed emitters. These emitter plates are to be heated to a certain temperature and/or by a given heat input and positioned at the front and/or rear burners of the range. The steady state tracer gas concentration is measured in three positions: at the test room inlet(s), at the extract air outlet and in the test room 0.5 m in front of the range at mid-height between range surface and hood. The CE can be determined with Eqn. 1.

2.3 Actual range hood performance tests

Besides reviewing recommended or previously known literature, a more systematic search using the phrases “range hood”, “kitchen ventilation” and “cooking exhaust” was performed within Web of Science. Publications older than 20 years, were excluded from a thorough review. There are a number of interesting publications from the National Taiwan University of Science and Technology investigating the performance of conventional, “air curtain”, “jet-isolated” and “quad-vortex” range hoods with the aid of tracer gas (SF_6) measurements and flow visualization using oil fumes (J. Chen, 2015; J. K. Chen, Huang, & Dai, 2010; R.F. Huang, Nian, & Chen, 2010; Rong Fung Huang et al., 2015, 2010; Liu, Wang, & Xi, 2014). They document the effects of potential range hood improvements and the influence of disturbing air flows or even the presence of a cook. Besides the analysis of the laser-sheet visualized flow patterns, the local tracer gas spillage concentrations are presented. However, global CE is mostly not provided. In summary, these experimental studies give very valuable insights on flow characteristics and potential measures to improve contaminant capture.

Experimental studies where the CE of commercially available range hoods was measured are summarized in Table 1. It lists: used performance metrics, number of tested devices and major results.

The main results of these studies are in good agreement and confirm what one would intuitively expect: higher CE for back burner use, for higher flow rates and for hoods with a big “sump”. These studies also shows that CE, in particular for front burner use, can vary drastically for different designs and that particle capture does not necessarily match CE efficiency for gaseous contaminants. Note that the later conclusion somewhat contradicts conclusions derived in (Beamer, Muller, & Dessagne, 1998). High potential for improvement was identified in terms of sound performance. For the tested models higher CE performance seemed to always correlate with high noise levels, seemingly a reason for occupants to not use the range hood (see 2.4).

Unfortunately, no scientific study was found that investigated the performance of recirculating ranges hoods. However, the leading German consumer magazine has recently tested 21 different range hoods in their extracting and recirculating configuration (Stiftung Warentest, 2016). Besides evaluating functionality, which included grease and odour removal performance tests based on ISO 61591 (and humidity removal in extracting modus), the assessment encompassed test criteria for sound, handling, energy consumption, versatility and safety. The results of the tests are categorized in five levels ranging from “very good” to “insufficient”. The results for grease removal in recirculation mode were either the same or dropped by one level compared to the extraction mode. However, the odour removal performance rating ranged mostly from “medium” to “insufficient” for recirculation, only one model was rated with “very good” and another model with “good”. In comparison, all models were rated “very good” for odour removal in extraction mode. Similar results can be observed in two older consumer tests by the same institution.

Table 1: Overview of publications on CE of commercially available range hoods

Study	Performance Metric	Test location, Type and Nr.	Results / Comments
B. C. Singer, Delp, Price, & Apte, 2012	CE (combustion product when heating pot of water) Airflow Sound	Field (15): Flat (5) Open Bowl (6) Hybrid (2) Downdraft (2)	Devices with flat bottom (no capture hood) have much lower CE CE is substantially higher for back burner use Flow rate and geometric coverage have also a large impact on CE A model to estimate CE from these parameters is derived
Rim, Wallace, Nabinger, & Persily, 2012	Whole house particle reduction effectiveness equivalent to CE (UFP produced by gas stove)	Field (2):	Higher flow rates generally increase UFP reduction Less reduction for smaller particles UFP reduction smaller for front burner, particle reduction 31% to 94%
Delp & Singer, 2012	CE (combustion product when heating pot of water) Airflow Sound	Lab (7): Basic (2) Compliant (1) Energy star (2) Microwave (1) Premium (1)	CE ranged from <15 to >98% Large open hoods perform best Front burner with CE>80% had sound levels too high for conversation Energy Star Hood had CE<30% for front burner
Yi et al. 2014	CE (Heat) CE (SF6 injected above pan with hot oil) CE not determined as “first pass” CE.	Lab (1)	CE for the combined use of kitchen ventilation (supply and extract) and extracting range hood CE of hood only around 50% Test chamber open on one side, concentration of entering air not recorded
Lunden et al., 2015	CE (PM from cooking) CE (combustion product)	Lab (4)	CE for back burner pan-frying (medium heat) mostly >80% and similar for PM and CO_2 CE for front burner stir-frying (high heat) varied by hood and airflow and were generally lower for PM capture
Claeys et al., 2015	CE (CO_2 injected above pot of boiling water)	Lab (1): Air curtain	CE reaches 77% at end of cooking event, but decreases after thermal plume of boiling water disappears Time-integrated CE is only 30%
Walker et al. 2016b	CE	Lab (8), Flat (4) Sump (4)	CE higher for lower mounting and greater depth from the wall
Simone et al. 2015	CE	Lab (1) Microwave	CE higher for back burners and lower temperatures
Farnsworth et al. 1989	NO_2 capture, H_2O capture,	Lab (7)	CE increases with air flow, and with use of side curtains. Separate capture of combustion products from cooking contaminants using special vented cooktop.

For evaluation of recirculating hoods, a different approach to the tracer gas CE discussed above is required. Instead we need to look at how well particular contaminants are removed, provide a controlled source for these contaminants and then design an experimental apparatus for laboratory evaluation. One possible approach is to use the technique used in previous studies where the cooking event is performed with and without the hood operating and the difference in room concentrations is used to estimate the removal by the range hood that could be converted into an equivalent capture efficiency.

2.4 Results from surveys

A number of surveys have been performed that give insights into characteristics of residential kitchen range hoods and/or the associated user-perceived performance (Chan, Kim, Singer, Walker, & Sherman, 2016; Klug, Lobscheid, & Singer, 2011; Klug, Singer, Bedrosian, & D'Cruz, 2011; Mullen, Li, & Singer, 2014; Singer, 2015). Figure 2 shows the answers to the questions "How often do you use range hood when cooking with cooktop?" and "What are the reasons for not using the kitchen range hood or exhaust fan?" from a study performed in California (Chan et al., 2016).

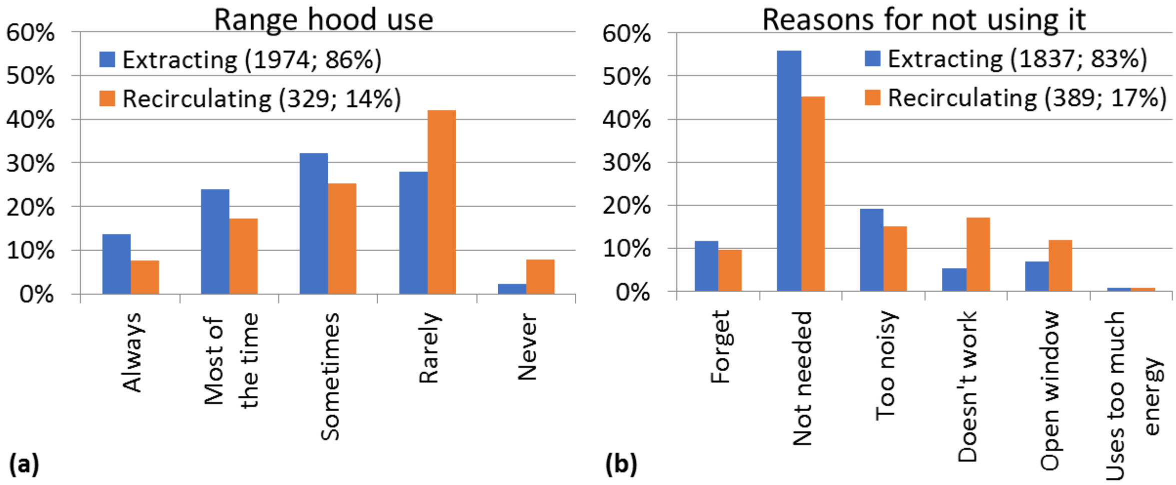

Figure 2: Survey results from (Chan et al., 2016) for the question "How often do you use range hood when cooking with cooktop?" (a) and "What are the reasons for not using the kitchen range hood or exhaust fan?" (b), segregated into households with extracting and recirculating cooking ventilation devices. The numbers in the legend refer to number and percentage of respondents in the respective category.

The results are segregated into households that had an extracting range hood or an extracting over-the-range microwave and households using a recirculating range hood or over-the-range microwave. Note that roughly 85% of respondents in this study used an extracting device. These data show a clear trend towards less usage for households with recirculating devices. And while both groups most frequently cite "not needed" as the reason for not using the hood, "Doesn't work" was cited by only 5% of respondents with an extracting device but cited by 17% of respondents with a recirculating device. This answer could refer to devices not operating at all, but some respondents might have chosen this answer to express "Doesn't work for removing odours/moisture". This hypothesis is strengthened by looking at the preliminary results from another online survey performed in 2014/15 (Singer, 2015). Herein the question "In your opinion, how effective is your kitchen fan?" was asked. Again, when segregated into groups with extracting and recirculating devices, 94% and 38% respectively, responded with "Very effective" or "Moderately effective". Only 6% of the households with extracting devices, but 58% of the group using a recirculating range hood chose "Not effective" as an answer. The small remainder of the respondents selected either "Fan is broken and does not work at all" or "No kitchen fan".

3 ENERGETIC COMPARISON

Based on the previous section one can say that further research is needed be able to evaluate the IAQ performance of recirculating range hoods. But what is the energetic benefit of installing a recirculating range hood in comparison to an extracting device? To answer that question a set of simple calculations were performed to estimate the difference in Primary Energy (PE) use for each of these two systems. The ventilation heat losses and the energetic impact of the required airflow openings were determined for an **extracting hood system**. The annual ventilation losses were calculated based on range hood airflow, heating degree hours and the estimated time the hood was in operation. Note that this estimation is conservative as does not account that the extracted air will be somewhat above room temperature. This assumes that the operation of the hood is evenly spread out throughout the year. The average infiltration air flow through the “unused” air openings was estimated using the empirical formula and data provided in (ASHRAE, 1993) for the effective leakage area L of a kitchen ventilation with closed damper:

$$\dot{V}_{inf} = \mathrm{L}\sqrt{\mathrm{A}\,\Delta\mathrm{T} + \mathrm{B}\,v^2} \tag{5}$$

The average temperature difference ΔT used to account for stack effects was determined for the months with an average ambient temperature <15°C and for an indoor temperature of 20°C. The average wind speed v was estimated to be 3 m/s for the reference case, 1m/s for the “min” case and 5 m/s for the “max” case. The stack and wind coefficient A and B for the “best estimate” reflect a two story house in moderate local shielding. The plausibility of the air flow results was compared to the calculated airflow of the effective leakage area model at 50 Pa using CONTAM and multiplied with the shielding coefficient e=0.07 from EN 832 (average shielding, >1 exposed façades). Both results were in good agreement. Recently, some manufacturers of air openings claim to have products specifically designed for low energy housing, e.g. (Naber, n.d.), which close airtight when the range hood is not in use. Therefore, no infiltrating airflow through the unused opening was applied as lower bound. The additional transmission losses due to the air openings were estimated as being the difference in heat transfer between a sheet metal plate and a wall with a U-value of 0.1 W/m²K (typical for PH) for an area corresponding to a Ø 150 mm opening. The U-value of the 1 mm thick sheet metal was increased by 20% to account for thermal bridge effects. The transmission losses turn out to be of minor relevance compared to the ventilation losses, justifying this simplified approach.

For the **recirculating system** aspects like, increased ventilation losses and fan power consumption for moisture (and possibly odour) removal via the MVHR, increased fan power consumption due to the increased pressure drop over the charcoal filter and embodied energy of the activated carbon were estimated. The increase in power consumption due to the carbon filter was determined based on the test results from a testing report (Stiftung Warentest, 2007). All 12 models were tested in extracting and recirculating mode, allowing the calculation of the difference in specific fan power (SFP) at highest setting. This difference in SFP multiplied by the assumed air flow and the time of operation gives the additional electricity consumption while assuming the same air flow. When the hoods are configured for recirculation they will not remove humidity generated during cooking. Additionally, the odour removal might not be sufficient and some occupants might want additional ventilation. This might be done by running the MVHR at a higher setting (or by opening a window). To account for this, the “best estimate” case assumes that one additional air exchange of the kitchen volume (35 m² x 2.5 m) is ventilated with a system having a heat recovery rate of 80% and a constant SFP of 0.45 Wh/m³. Note that non-linear increase of the power consumption due to increase in pressure drop at higher flows is not accounted for. The “min” / “max” case assume that only 0.5 / 2 air exchange(s) are needed by the occupant and that the kitchen volume has 38 m³ / 150 m³. The embodied primary energy contained in activated carbon is in the order of 20 MJ/kg, e.g. (Zanoletti et al., 2017). Assuming that the filters contain 150 g / 300 g and 4000 g (as one of the models in the fore mentioned test) of activated carbon with a proposed change interval of 3 / 2 / 1 time(s) per year, the embodied energy is calculated for the three scenarios "min" / "best estimate" / "max". For all of the described calculations a Primary Energy (PE) factor of 1.1 is used for thermal energy and a factor of 2 is used for electric energy.

Figure 3 shows the calculated PE for the described aspects for extracting and recirculating range hoods. The "best estimate", minimum and maximum scenarios are depicted for each category. Depending on range hood use, ventilation losses from extraction clearly dominate the other loss mechanisms and could be problematic when trying to reach the PH heating demand criteria of 15 kWh/m²a. The use of tightly sealing air openings would help reduce the PE use associated with the extraction hood by around 30% for the "best estimate" case. If users of a recirculating range hood end up needing a lot of extra ventilation, the energy use could in theory end up being higher than with an effective extracting system. The subjective need for additional ventilation will strongly depend on the occupants and their odour perception and the effectiveness of the recirculating range hood in removing odours. The need for humidity removal will depend on climates, but should not be an issue in houses with continuously running mechanical ventilation, as the relative humidity tends to be rather low for those located in heating dominated climates, e.g. in Central Europe (Rojas, 2015). The question remains on how well recirculating range hoods remove health related contaminants, like particles generated through cooking. These calculations also show that the embodied energy and the additional pressure drop of the AC filter, as well as the transmission losses of the air openings of an extracting solution will typically not strongly impact the PE balance.

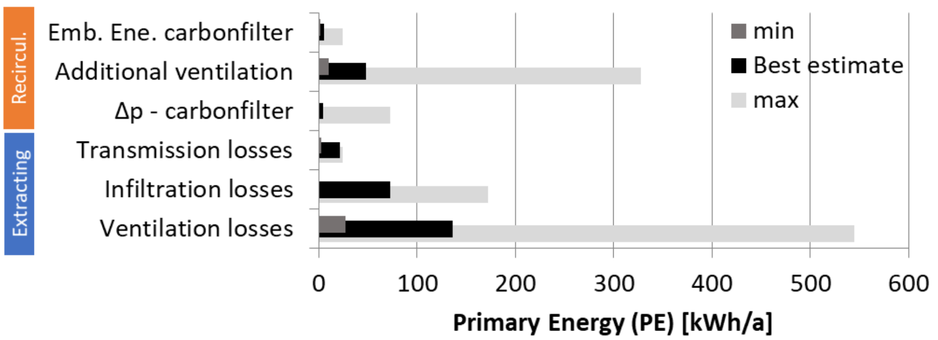

Figure 3: Differences in Primary Energy use for various aspects related to the use of extracting and recirculating range hoods.

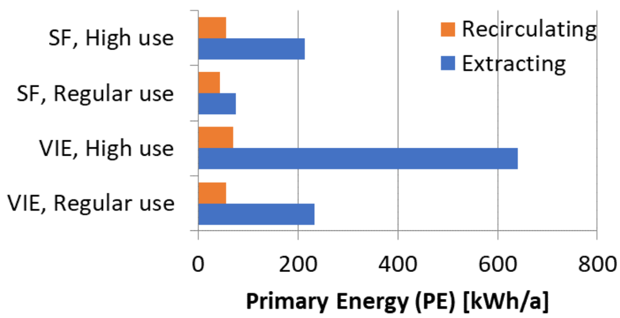

Figure 4: Differences in Primary Energy use related to the use of extracting and recirculating range hoods. The four scenarios represent the climate of San Francisco (SF) and Vienna (VIE) and regular and high usage of the range hood (time per day and flow setting).

Figure 4 shows the total PE when the "best estimate" scenario is applied for the representative climate of Vienna and San Francisco (taken from PHPP (Passive House Institute, 2013)) assuming a regular use (30 min/day at 250 m³/h) and a high use (60 min/day at 500 m³/h). It shows that for regular use and climates with moderate heating demand there is no reason to install a recirculating range hood from an energetic point of view. This differs for colder climates and in particular for high use scenarios. Here, the reduction in heating demand could be substantial for low-energy housing.

4 CONCLUSIONS

A good number of studies exist which have investigated the performance of extracting range hoods in residential settings and the associated exposure to cooking contaminants. The focus has been on pollutants resulting from gas combusting ranges and/or the cooking generated particles. However no scientific study investigating the performance of recirculating range hoods, as often installed in highly energy efficient homes, was found. Open questions remain on their effectiveness in removing cooking generated particles and organic (odorous) contaminants. Results from user surveys in the US indicate that low performance is, amongst others, a reason why people don’t use their recirculating kitchen ventilation.
The existing test standard (ISO) applicable to recirculating devices covers grease adsorption and removal of a certain chemical (MEK). However performance test are needed to characterize effectiveness in reducing exposure to cooking generated PM and VOC’s, in particular as the AC filter ages. A simple energetic comparison shows that for climates with distinct heating demand and for scenarios of high use (time and air flow) recirculating range hoods can substantially reduce energy use associated with cooking ventilation.
The main conclusion is that further research on the performance of recirculating range hoods in terms of IAQ is urgently needed.

5 ACKNOWLEDGEMENTS

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