Indoor Air Pollution, Passive Ventilation Strategies and Thermal Comfort in Nepal

A study of the association between ventilation, indoor air quality and operative temperature in rural high altitude settlements

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Master thesis for the Department of Architecture and Built Environment: Division of Energy and Building Design

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Master Thesis

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Abstract

Indoor Air Pollution (IAP) resulting from indoor burning of solid biomass fuels in poorly ventilated kitchens is a severe health risk in parts of the world where energy poverty is prevalent. Passive ventilation, i.e. taking advantage of naturally induced airflow has been suggested as crucial in reducing IAP levels below safe limits. Residents in high altitude settlements are however exposed to extreme cold climatic conditions hence the employment of natural ventilation risk to be limited by behavioral practices as well as climate responsive design of the vernacular architecture aiming to minimize heat losses.

Based on a case study of the high altitude village of Chame, Manang, stove usage and ventilation patterns as well as common architectonic features of 25 households were documented. Ventilation rates for hypothetical kitchens with three different opening configurations were simulated. Resulting indoor concentrations of carbon monoxide (CO) were estimated by applying a simplified single-zone model approach and evaluated with respect to Indoor Air Quality (IAQ) guidelines stated by the World Health Organization (WHO) as well as national Nepalese guidelines. Annual frequencies and diurnal dynamics of indoor operative temperatures were further simulated in order to investigate the impact of ventilation efficiency on indoor thermal comfort.

The results suggest that indoor concentrations of CO in high altitude settlements with similar architectonic features, stove usage and ventilation practices as assessed in this study risk to exceed health deteriorating limits. It is however shown that increasing natural ventilation by only intervening in the building structures applying different opening designs has the potential to enhance ventilation efficiency and thereby reduce CO levels significantly.

The expected inverse correlation between indoor air quality and indoor thermal comfort was confirmed and quantified. The findings further support that residents in the Himalayan region live far below internationally recognized comfort standards. Building envelopes providing a stable and resilient indoor thermal climate are hence predicted to encourage residents to take advantage of natural ventilation when needed, limiting the trade-off between keeping warm at present versus long term health impacts. Reversibly, higher ventilation rates during stove usage would diminish the need to keep openings opened after the stove is extinguished in order to avoid a prolonged exposure to elevated IAP levels, which in turn would reduce ventilation associated heat losses.

Energy efficient building techniques reducing the need for space heating and opening configurations providing adequate prerequisites for sufficient passive ventilation are hence suggested as important parameters in preserving indoor thermal comfort as well as limiting the exposure to elevated IAP levels in biomass dependent households of high altitudes. Associated social, economic and environmental values would be of great importance in the strive towards a sustainable development of the Nepalese society.

Executive summary

Introduction, motivation and objectives
Indoor Air Pollution (IAP) resulting from indoor burning of solid biomass fuels is a severe environmental health risk in Nepal as well as in other parts of the world where energy poverty is prevalent. Passive ventilation strategies, i.e. taking advantage of natural driving forces to induce airflow rates through the building envelope, has thus been suggested to be crucial in reducing IAP levels below safe limits. Moreover, residents in high altitude settlements in the Himalayan region are exposed to extreme cold climatic conditions and have been reported to live far below comfort standards as internationally would be recognized as acceptable. The employment of natural ventilation thus risk to be restricted by both climate responsive architectonic features as well as behavioral practices aiming to preserve indoor thermal comfort.

As a spin-off from a larger study aiming to assess thermal comfort in Nepalese residential buildings, conducted parallel to the EU-initiated CIMCEB project concerning *Energy Efficient Building*, this thesis provides an investigation of stove usage and ventilation patterns and how the employment of different passive ventilation strategies affect the resulting concentrations of IAP as well as impact indoor operative temperatures in Nepalese high altitude settlements. The overall purpose of this thesis is to establish a link between architecture, passive ventilation, IAP and thermal comfort, evaluated in a holistic perspective of the importance of energy efficient building and a sustainable energy supply.

The correlation between high IAP levels, insufficient ventilation and health impacts is well established in literature. However, studies assessing the potential of natural ventilation as a mean *per sé* to reduce IAP are found scarce. Moreover, as far as the author of this thesis is concerned, the link between stove usage, ventilation patterns and the resulting impact on indoor thermal comfort has never been investigated. Similarly, neither has a systematic assessment of the correlation between stove usage and ventilation patterns previously been conducted in Nepal.

Method
An interdisciplinary four-step research process was conducted in the format of a case study of the high altitude settlement of Chame, Manang. IAP levels were estimated by using carbon monoxide (CO) as an indicator pollutant in a simplified single-zone model, of which architectonic features were derived from an interview study providing information on most common opening situation and general physical features derived from 25 surveyed kitchens. Air exchange rates (AER) were calculated for hypothetical kitchens with different opening configurations based on simulated weighted annual averages of airflow rates including site specific data on local climatic conditions and common construction materials. Emission rates and the amount of radiant heat generated by the stove was based on values reported in literature aiming to correspond to the most common stove and fuel combination observed in Chame. Variations in stove performance observed in field was accounted for by assessing CO levels for a range of fugitive emissions entering the indoor environment. Resulting concentrations of CO were evaluated for each case with respect to Indoor Air Quality (IAQ) guidelines stated by World Health Organization (WHO) as well as national Nepalese guidelines. The dynamic correlation between ventilation efficiency and indoor thermal comfort was thereby assessed by simulating annual prevalence and diurnal dynamics of operative temperatures resulting from the different opening configurations, including seasonal stove usage and ventilation patterns assessed by the interview study.

Results
The findings of the interview study confirm that the majority of the surveyed households in the high altitude village of Chame are reliant on solid biomass to cover annual energy needs, of which wood-fired Improved Cooking Stoves (ICS) were found to be the most common cooking and heating device. A consistent correlation was found between stove usage and the practice of opening openings summer as well as winter, indicating a desire to reduce smoke accumulation during stove usage activity which was further confirmed by smoky kitchens observed on site. A seasonal difference in occupant behavior was however recorded, with extended stove usage and restricted ventilation patterns during winter.

The IAP assessment suggests that indoor concentrations of CO in high altitude settlements with similar architectonic features, stove usage and ventilation practices as investigated in this study risk to exceed health deteriorating limits. This despite the presence of improved cooking stoves fitted with chimneys, if the lack of improved features, frequent maintenance and improper operation as observed in field fall within the same range of fugitive emissions as examined. Under the pretext that the average chimney-stove emission reduction potential of 69 % derived from literature represent the situation observed in Chame, indoor concentrations of CO in the kitchen with an opening configuration representing the current ventilation situation risk to exceed permissible average concentrations stated by WHO for the duration of 1 hour and 8 hour exposure with a factor of 2 and 7, respectively.

It is however shown that increasing natural ventilation by only intervening in the building structures applying different opening designs has the potential to reduce indoor concentrations of CO significantly. Increasing the opened area of single sided ventilation with around 100 % is shown to increase airflow rates with 60 %, resulting in a reduction of CO levels with 39 % during stove usage activity. Employing cross ventilation by adding a window of the same size to an opposite facing wall result in a higher increase of airflow rates of 100 % compared to the base case, reducing indoor CO concentrations with 51 %.

Nonetheless, considering the chimney reduction potential of 69 %, only cross ventilation showed to reduce CO levels below safe limits with respect to 1 hour IAQ guidelines. Moreover, no opening configuration investigated in this study ensure IAP levels below 8 hour IAQ guideline values for any level of fugitive emission. It is thereby reconfirmed that the severity of the health risks associated with the elevated IAP levels presented in this study is dependent on total time of exposure.

The expected inverse correlation between ventilation efficiency and indoor thermal comfort was further confirmed. This can be seen in both annual prevalence as well as diurnal dynamics of operative temperatures in the kitchens with different opening configurations. Indoor operative temperatures (T_{op}) were however shown to fall below 10 ^{o}C for a substantial part of the year and below 0 ^{o}C during colder winter days for *all* opening configuration cases. This is both attributed to that current ventilation practices result in that T_{op} coincide with low ambient temperatures during the day, as well as the poor thermal resistance of the building envelopes observed in Chame and hence employed in the simulations. These findings hence confirm that residents in the Himalayan region risk to live far below internationally recognized comfort standards. As a result, the magnitude of thermal *dis*comfort was assessed and related to ventilation efficiency: the higher airflow rates provided by increasing the opened area of single sided ventilation and employing cross ventilation were documented to result in a 5 % and 6 % higher annual frequency of hours with T_{op} falling below 10 ^{o}C, respectively.

Recommendations and conclusions
Considering the performance in reducing indoor accumulation of toxic substances during stove usage activity, cross ventilation is preferred over increasing the opened area of single sided ventilation. This due to the higher ventilation efficiency provided, ensuring IAP levels below safe 1 hour IAQ guideline values for the highest levels of fugitive emissions. The most prominent hourly fluctuations of indoor operative temperatures were however shown for the case of cross ventilation, suggesting that indoor thermal comfort is subject to a higher level of influence by instant changes in local climate conditions such as rapid changes in prevailing winds than a kitchen with single sided ventilation. This is also of importance considering resulting IAP levels, since temporary low wind speeds in summer were shown to reduce the wind effect which risk to compromise the performance in providing sufficient airflow rates to ensure a healthy indoor air quality. Reversibly, too strong winds might prevent the cross ventilating window to be opened which also would result in higher IAP levels. As a result, this study suggests that including considerations for site-specific characteristics of local climatic conditions is vital in the design and application of alternative opening configurations. This in order to ensure that physical prerequisites as well as behavioral practice allow for sufficient airflow rates for passive ventilation to be successful in preventing accumulation of IAP.

In order to reduce the risk for a prolonged exposure to health deteriorating levels of IAP, the opening configurations examined in this study are required to be kept opened a short while after the stove is extinguished also at night to meet 8 hour IAQ guidelines. The feasibility of changing behavioral practices is however dependent on the residents' perception of the problem of smoke accumulation, and the resulting priority of preserving the heat generated by the stove at present versus potential future health impacts resulting from an extended exposure to IAP. Nonetheless, a more restricted ventilation pattern between morning and afternoon stove usage than what was documented to be common practice in Chame is required to prevent indoor operative temperatures to fall below 0 ^{o}C during cold winter days. To eliminate the need of keeping openings opened after stove usage and thereby limit associated heat losses, opening configurations allowing for larger ventilation rates during stove usage activity than what has been examined in this study are required.

As a result, this study confirms that there is a conflict between a healthy indoor air quality and preserving indoor thermal comfort in biomass reliant households where fugitive emissions exceed permissible levels for safe health. For kitchens with opening configurations only allowing for a limited natural ventilation, characteristics of the source of pollution considering stove design and proper operation become more important since these parameters affect the magnitude of fugitive emissions and hence the need for extended ventilation patterns.

It is however concluded that in order to improve indoor air quality and thermal comfort by intervening in the living environment in Nepalese high altitude settlements, *both* energy efficient building techniques considering physical parameters of the house construction as well as efficient passive ventilation strategies (including both opening design and behavioral patterns) are required. Building envelopes with a higher thermal resistance providing a stable thermal indoor environment resilient to dynamic fluctuations of the surrounding climate are predicted to have the potential to facilitate the encouragement of residents to keep openings opened a short while after stove usage at night. This since the trade-off between keeping warm at present versus future health impacts would be limited. More airtight homes would however require a thorough consideration for

opening configurations allowing for sufficient ventilation rates. On the other hand, opening configurations providing a higher ventilation efficiency during stove usage would further reduce the need to keep openings opened after the stove is extinguished to meet IAQ guidelines, and thereby prevent ventilation associated heat losses.

Understanding the inverse correlation between architecture, natural ventilation, health and indoor thermal comfort hence becomes of great concern in the development of a new Nepalese building standard, initiated by the government in the wake of the devastating earthquake 2015. If the energy poverty prevails and access to and successful implementation of cleaner cooking technologies do not emerge simultaneously, improving thermal comfort by employing energy efficient building strategies providing airtight homes risk to further aggravate the problematic issue of IAP. This insight indicates the necessity of having a holistic approach when aiming to improve living conditions for biomass reliant households in high altitude regions. As a result, except from providing new house constructions with opening configurations allowing for sufficient and energy efficient natural ventilation, informing residents about efficient passive ventilation strategies is also suggested as a vital step towards improving societal health in high altitude regions in Nepal, including both aspects of indoor air quality and thermal comfort.

Furthermore, in the light of a predicted biomass dependence the coming decades, a warmer indoor climate in high altitude settlements provided by energy efficient building techniques and efficient passive ventilation strategies are associated with both social, environmental and economic values. A reduced need for space heating would limit the risk for a prolonged exposure to elevated IAP levels as well as reduce fuel consumption. A reduced fuel consumption is in turn of great significance when it comes to restraining the ongoing deforestation in Nepal as well as a question of household economy. Since women in Nepal are traditionally responsible for household cooking activities and spend a substantial part of the day collecting fuel, reducing energy demand for heating purposes also becomes a question of health equality and mitigating the burden of domestic labor.

Conclusively, this thesis establishes a link between architecture, passive ventilation, indoor air pollution and thermal comfort in Nepalese high altitude settlements, exemplifying the essence of a sustainable energy supply within the concept of energy efficient building; two crucial parameters in reducing the extensive use of solid biomass fuels, which in turn is required in the strive towards a sustainable societal development in Nepal.

Key words: *Energy poverty, Solid biomass fuels, Improved cooking stoves, Indoor air pollution, Carbon monoxide, Vernacular architecture, Passive ventilation, Air exchange rate, Indoor air quality, Thermal comfort, Operative temperature, Sustainable societal development.*

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Abbreviations and units

Abbreviation	**Description**	**Unit**
$ACAP$	Annapurna Conservation Area Project	$-$
$AEPC$	Alternative Energy Promotion Center	$-$
AER	Air Exchange Rate	h^{-1} or s^{-1}
CE	Combustion Efficiency	%
CO	Carbon monoxide	$-$
C_t	Accumulated concentration	g/m^3
C_{t+1}	Concentration at time t	g/m^3
E_f	Emission factor	g/s
E_r	Emission rate	g/s
F_{rate}	Fuel burning rate	g/kg
HTE	Heat Transfer Efficiency	%
ICS	Improved Cooking Stove	$-$
IAP	Indoor Air Pollution	$-$
IAQ	Indoor Air Quality	$-$
LHV	Lower Heating Value	MJ/kg
$m.a.s.l.$	Meters above sea level	m
OTE	Overall Thermal Efficiency	%
PM	Particulate Matter	$\mu g/m^3$
PIC	Product of Incomplete Combustion	$-$
T_{op}	Operative Temperature	^oC
TCS	Traditional Cooking Stove	$-$
Q	Airflow rate	l/s
V	Volume	m^3
W_{dir}	Wind direction	^{o}
W_{speed}	Wind speed	m/s
W_{stove}	Stove power	W
WHO	World Health Organization	$-$
σ	Chimney capture efficiency	%

Contents

1 INTRODUCTION

1.1 Motivation

Creating a sustainable society is a currently a hot topic in the global political agenda. Given that the definition of sustainability comprises both social, environmental and economic dimensions, the complexity lies in finding holistic solutions to intertwined societal challenges. The issue of energy is a key example of such a challenge in which all dimensions of sustainability are concerned (The World Bank 2011; United Nations 2018b). This is valid for both industrial as well as developing countries. Consequently, feasible energy solutions are products of compromises between the different pillars of sustainability where national prerequisites determine the order of priority.

Around a third of the world's population is dependent on solid biomass fuels (e.g. wood, dung, agricultural wastes) to cover their energy needs (United Nations 2018b). In Nepal, as in the majority of other developing countries, these fuels are burnt indoors while cooking on open fires or traditional stoves often without sufficient ventilation, emitting toxic substances resulting in health impacts where respiratory diseases are prominent (Oluwole et al. 2012; Joshi, Pandeya, and B. Dhakal 2009; Surendra et al. 2011; Malla 2013; World Health Organization 2000; Goldemberg 2000; Pokhrel et al. 2015; Parajuli, H. Lee, and K. Shrestha 2016). As a result, World Health Organization (WHO) currently declared Indoor Air Pollution (IAP) as the most important environmental health risk in the global community, being responsible for approximately 4 million premature deaths each year (World Health Organization 2015; United Nations 2018b).

The accumulation of health damaging IAP has been closely linked to poorly ventilated kitchens (Parajuli, H. Lee, and K. Shrestha 2016). Given the economic situation in Nepal, it has been suggested that controlling ventilation is the most economically feasible way to improve Indoor Air Quality (IAQ) in Nepalese rural households, since switching to cleaner stoves and fuels are non-affordable for many rural families today. Passive ventilation strategies, i.e taking advantage of natural driving forces to induce airflow through the building envelope, have thus been stated as a cost efficient and rapidly employable measure on reducing IAP levels below safe limits (Cowlin 2005; Parajuli, H. Lee, and K. Shrestha 2016).

However, Nepal is a country which covers several different climate zones (Central Bureau of Statistics 2012; Bodach, Lang, and Hamhaber 2014). Situated in the heart of the Himalayan mountain range, rural settlements located on high altitude are exposed to extreme conditions in terms of cold (H. Rijal, Yoshida, and Umemiya 2010). Despite reports on climate responsive design in high altitude vernacular architecture aiming to preserve thermal comfort (Parajuli, H. Lee, and K. Shrestha 2016), small differences between indoor and outdoor temperatures have been recorded (H. Rijal, Yoshida, and Umemiya 2010). As a result, discomfort, illness and even death are claimed to have been correlated to harsh indoor climatic conditions in colder regions of Nepal (H. Rijal, Yoshida, and Umemiya 2010). Residents are thus forced to employ various adaptation measures to cope with dynamic climatic conditions, among which burning firewood is common in colder climates (H. Rijal, Yoshida, and Umemiya 2010).

1.2 Problem statement

Residents in the Himalayan region live far below comfort standards that internationally would be recognized as acceptable (Fuller, Zahnd, and Thakuri 2009). Stove usage and ventilation patterns are two factors influencing both IAP levels as well as the indoor thermal comfort. Thus, the employment of sufficient natural ventilation risk to be restricted by both behavioral practices as well as climate responsive architectonic features aiming to provide a comfortable indoor environment considering the surrounding climate.

The complexity is clear. High altitude settlements dependent on solid biomass fuels face the trade-off between keeping warm and inhaling health deteriorating air pollutants. Is the strive to maintain an acceptable indoor thermal environment at present, prioritized over long term health impacts resulting from exposure to IAP? How much ventilation would be required in order to meet indoor air quality guidelines for safe health, and how would this affect indoor thermal comfort? Does the current architecture allow for the required airflow rates considering prevalence and placement of openings, and is this used?

1.2.1 A gap in research

The correlation between high IAP levels, insufficient ventilation and health impacts is well established in literature. However, studies assessing the potential of natural ventilation as a mean *per sé* to reduce IAP are found scarce. Moreover, as far as the author is concerned, the link between stove usage, ventilation patterns and thermal comfort has never been investigated. Similarly, neither has a systematic assessment of the correlation between stove usage and ventilation patterns previously been conducted in Nepal.

1.2.2 Objectives

This thesis is a spin-off of the larger EU-initiated CIMCEB project, a collaboration between Austria, Bhutan, Estonia, Nepal and Sweden in the deployment of master programmes in *Energy Efficient Building*; a concept characterized by employing architectural features and construction materials aiming to maintain a comfortable indoor environment with the least energy input possible. In light of the development of a new Nepalese building standard, initiated by the government in the wake of the devastating earthquake 2015, a report on the present thermal comfort as well as associated advantages of enhancing the indoor thermal climate could be of importance considering a future urban as well as rural sustainable development. Hence, this project serves as an investigation on factors influencing thermal comfort in Nepalese households, and aims to highlight further benefits of improving indoor thermal conditions in a holistic perspective, by coupling energy, architecture and behavioral patterns to societal health. More concretely, the aim with this thesis is to:

- **Investigate** and **identify** stove usage and ventilation patterns in high altitude settlements of Nepal
- **Assess** the ventilation efficiency of the current ventilation situation considering the accumulation of IAP generated by indoor burning of solid biomass fuels with respect to international and Nepalese standards on indoor air quality
- **Examine** the efficiency of alternative passive ventilation strategies considering the ability to reduce the accumulation of IAP to not exceed international and Nepalese guideline values for indoor air quality
- **Evaluate** the current ventilation situation as well as alternative passive ventilation strategies considering the performance in reducing IAP levels and the resulting impact of ventilation efficiency on indoor thermal comfort

Purpose statement

Thus, the overall purpose with this thesis is to establish a link between indoor air pollution, passive ventilation strategies and thermal comfort in Nepalese high altitude settlements within the context of energy efficient building; a concept which is essential in the strive towards a sustainable energy supply where reducing the need for the extensive use of biomass fuels is predicted to have both social, environmental and economic values. A conceptual chart displaying the scope of this thesis is presented in Figure 1.

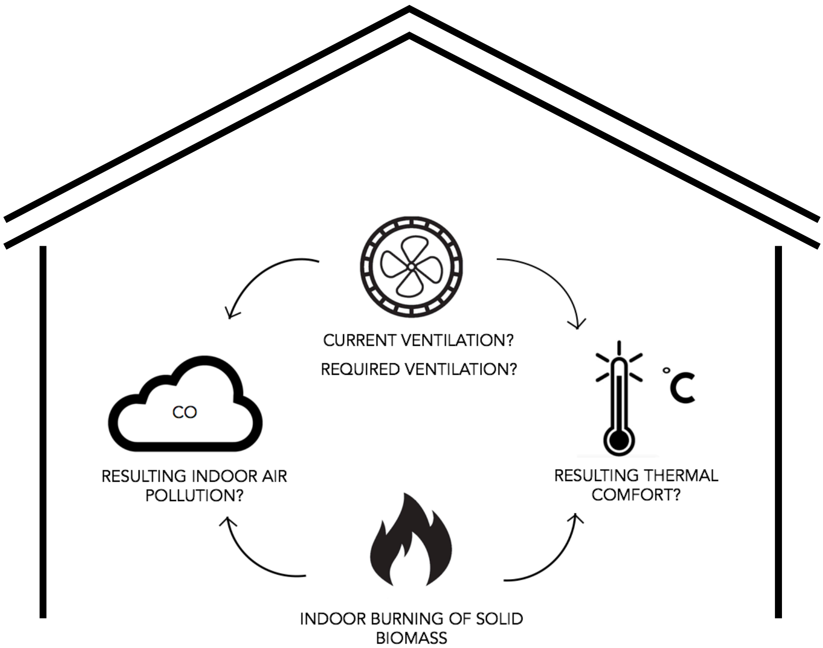

Figure 1: Conceptual chart of the scope of this thesis illustrating the complex inter-correlation between stove usage and natural ventilation considering the impact on indoor air quality and thermal comfort.

1.2.3 Academic contributions

WHO has called for a systematic population-based approach to assessing fuel use patterns and resulting exposure to air pollution in a wide range of communities where IAP is a serious hazard (World Health Organization 2000). Additionally, to further enhance the accuracy of models used to assess the correlation between technology generated emissions and indoor air quality, the need for region-specific data on kitchen volumes, device usage time and air exchange rates has currently been expressed (World Health Organization 2015). More specifically, WHO presents modeling of improvements in ventilation as a key factor in establishing the link between household energy use and indoor air quality (Johnson, Edwards, et al. 2014).

As a result, an assessment of stove usage and ventilation patterns in Nepal is not only valuable for the investigation of factors influencing thermal comfort for similar comfort studies. Rather, an improved understanding of behavioral patterns affecting the indoor thermal climate will facilitate more accurate projections of household energy demand and resulting indoor air quality (Johnson, Edwards, et al. 2014), an essential factor in moving towards a more sustainable Nepalese energy supply respecting both environmental, economic and social aspects (Malla 2013). The intended academic contributions of this thesis are further summarized below:

- Improving understanding on residential behavior regarding stove usage practices, the employment of passive ventilation and the inter-correlation between the two activities

- Improving understanding on the magnitude of ventilation required during indoor burning of solid biomass in order to not exceed limit values for health impacts associated with resulting IAP

- Providing an evaluation of different opening configurations considering ventilation efficiency and a quantification of the respective influence on indoor thermal comfort in Nepalese high altitude settlements

Furthermore, an increased understanding of the interrelationship between household energy consumption and health risks is dedicated to facilitate the development of holistic strategies aiming to improve living conditions within the built environment for biomass reliant households to ensure for public health, which in turn is stated as a crucial prerequisite for economic development in developing countries (Balakrishnan, Ramaswamy, and Sankar 2004).

1.3 Limitations

The main limitations of this thesis comprise:

- **Scope of study:** Due to the limited time allocated to examine different ventilation strategies, this thesis does not cover an optimization of naturally induced airflow rates. Rather, the relative influence of different opening configurations on resulting airflow rates are assessed and evaluated with respect to IAP levels and impact on thermal comfort, nonetheless providing a combined evaluation of the correlation between ventilation efficiency and indoor thermal conditions.

1.4 Delimitations

The main delimitations of this thesis comprise:

- **Geographical region:** This study is focused on high altitude settlements in Nepal hence no general conclusions for all Nepalese households can be drawn from the results provided, given that regional differences in climate, culture and religion all influence local building practices as well as behavioral patterns in Nepal.

- **Interventions:** The investigation of alternative passive ventilation strategies' performance in reducing IAP levels and the respective influence on indoor thermal comfort does not include a change in behavioral practice in terms of point in time or duration of keeping openings opened. Increasing natural ventilation by only intervening in the physical building structure applying different opening designs are examined.

- **Validity of results:** Measurements and monitoring of pollutant concentrations and indoor thermal properties in rural kitchens were not conducted due to limited time and resources. Rather, the findings of this research are based on simulations and calculations performed for hypothetical kitchens of which architectonic features, household characteristics and behavioral patterns are derived from empirical data and most common observations. As a result, the results presented are not to be considered as *exact* or valid for specific households.

- **Processing of empirical data:** No statistical determination of the prevalence of households risking to exceed indoor air quality guideline values such as provided by a *Monte Carlo* simulation is presented. This since the scope of this thesis comprise qualitative simulations based on a limited number of hypothetical kitchens developed from a general case aiming to represent common architectonic features documented in field, rather than evaluating the situation and improvements for *all* units in the survey sample.

- **Health assessment:** No cause-effect relationship between resulting IAP levels and health impacts is provided given that a health-status survey fall beyond the scope of this study. The evaluation of resulting IAP levels considering potential health risks is hence conducted with respect to indoor concentrations of an indicator pollutant put in relation to Indoor Air Quality (IAQ) guidelines formulated by WHO as well as the Nepalese government. It should further be noted that the estimations of IAP levels provided are not equivalent to personal exposure, since the latter is dependent on additional behavioral factors and potential contributions from other sources of pollution.

1.5 Outline of the report

Chapter 1 is the introduction of the report, where the motivation, problem statement, objectives, limitations and delimitations of this thesis are presented. Chapter 2 gives an outlook and overview of the context in which this study is performed and hypotheses are formulated, followed by Chapter 3 which describes the theory upon which the research methods are based. Two chapters are designated to describe the methodology, analytical approach and methods applied in this thesis: Chapter 4 presents the methodology rationale and analytical approach providing an overview of the general research strategy applied to answer the research questions, followed by Chapter 5 outlining the specific methods used. Results are presented in Chapter 6, of which a partitioned analysis and discussion follows in Chapter 7. Research questions are explicitly answered in Chapter 8, which together with overall conclusions and personal reflections constitute the final part of this thesis.

2 BACKGROUND

2.1 Indoor Air Pollution (IAP)

2.1.1 A global outlook

More than a third of the world's population − around 3 billion people − are dependent on solid biomass fuels (e.g. wood, dung, agricultural wastes) to cover their daily energy needs (United Nations 2018a). This is a result of energy poverty, defined as the lack of existing infrastructure of clean and modern energy services (Rehfuess 2006). The reliance on biomass fuels for cooking and heating purposes is thus a common feature of rural households in developing countries (World Health Organization 2015).

There is unequivocal evidence that residents in households reliant on solid biomass are exposed to high levels of health hazardous pollutants (Balakrishnan, Mehta, et al. 2014). Combustion of solid biomass emits several toxic substances such as particulate matter, carbon monoxide, nitrous oxides, sulfur oxides, formaldehyde and carcinogenic polycyclic organic matter (World Health Organization 2000; Rehfuess 2006). These fuels are burnt indoors while cooking on open fires or traditional stoves, often without sufficient ventilation, resulting in indoor accumulation of stove generated toxic substances (Joshi, Pandeya, and B. Dhakal 2009; Malla 2013; World Health Organization 2000; Goldemberg 2000; Pokhrel et al. 2015; Parajuli, H. Lee, and K. Shrestha 2016).

Previous studies have reported on average indoor concentrations of IAP being up to 10 to 20 times higher than permissible values for safe health according to Indoor Air Quality (IAQ) guidelines provided by WHO (Still et al. 2011). Small particles of particulate matter with a diameter of less than 2.5 μm ($PM_{2.5}$) are considered as especially dangerous since the small and volatile nature have the capability to reach deeply into the lungs (Ranabhat et al. 2015; World Health Organization 2000). As a result, acute respiratory infections (ARIs), chronic obstructive pulmonary disease (COPD) and lung cancer have been correlated to exposure of pollutants from household biomass combustion (Ranabhat et al. 2015; World Health Organization 2000; I. L. Shrestha and S. L. Shrestha 2005).

More specifically, health effects correlated to indoor combustion of biomass have been categorized into the four following groups, as presented by Goldemberg (2000) based on Smith (2000)'s findings where level of evidence is included:

1. **Infectious respiratory diseases:** Acute respiratory disease (ARI) and tuberculosis (sufficient evidence)

2. **Chronic respiratory diseases:** Bronchitis and lung cancer (sufficient evidence)

3. **Adverse pregnancy outcomes:** Stillbirth and low birth weight in babies born to women being exposed to IAP during pregnancy (low confidence)

4. **Blindness, asthma and heart disease** (low confidence)

2.1.2 Global recognition

"Day in and day out, and for hours at a time, women and their small children breathe in amounts of smoke equivalent to consuming two packs of cigarettes per day" (Rehfuess 2006)

Indoor air pollution associated with indoor burning of biomass fuels has been declared as a severe threat to public health in the global community. In the year of 2000, indoor burning of solid biomass fuels was counted as one of the top ten global health risks, ranked right after malnutrition, unsafe sex, lack of clean water and adequate sanitation (Rehfuess 2006). Nonetheless, the United Nations did not explicitly outline eradicating energy poverty as a *Millennium Development Goal*. Access to clean energy first came to be recognized as a crucial part of sustainable development at the *World Summit on Sustainable Development* held in Johannesburg in 2002 (United Nations 2018b).

International development agendas have thus been claimed to fail regarding addressing the severity of the link between access to clean energy, human health and societal development. This despite the fact that the problematic issues related to indoor air pollution can be dated back to the early days of human settlements (Rehfuess 2006). In 2006, WHO officially declared IAP resulting from indoor burning of solid biomass fuels for cooking and heating purposes as a neglected health problem being an obstacle in reaching several of the *Millennium Development Goals* (Rehfuess 2006).

However, in 2011 the United Nations' *Sustainable Energy for All* initiative highlights the importance of clean energy in the strive towards a sustainable development and sets out a framework with the following three main objectives for 2030 (United Nations 2018b):

- Providing universal energy access to modern energy services
- Doubling the global rate on improvement in energy efficiency
- Doubling the share of renewable energy in the global energy mix

In 2014, WHO addressed IAP resulting from household combustion of biomass as the most important global environmental health risk, being responsible for around 4 million premature deaths each year (World Health Organization 2015; United Nations 2018a). Consequently, the problematic issue of IAP gained recognition in the international public health agenda, and energy is now a separate goal of the current *Sustainable Development Goals* (SDGs) of the *2030 Agenda for Sustainable Development* adopted in 2015, pursuing to ensure access to "affordable, reliable, sustainable and modern energy for all" (United Nations 2018b).

2.1.3 Global action

Stepping up the energy ladder in terms of switching to cleaner fuels and stoves is tightly correlated to the increase of income (Fuller, Zahnd, and Thakuri 2009; Malla 2013; The World Bank 2011). Due to the fact that even a doubling of a general income in a developing country has been estimated to only reduce global biomass usage by 16 %, the dependence on solid biomass fuels in countries with prominent energy poverty is predicted to remain the coming decades (Fuller, Zahnd, and Thakuri 2009; Malla 2013; The World Bank 2011), unless strong policy measures on improving access to alternative energy sources and services are employed (Ranabhat et al. 2015).

As a result, the distribution of *Improved Cooking Stoves* (ICS) has been widely implemented world-wide aiming to reduce biomass fuel consumption and exposure to IAP (The World Bank 2011). However, the success of implementing an ICS considering reducing IAP levels is widely debated due to the lack of a distinct definition of the improved features and thus varying quality of the IAP reduction potential compared to traditional cooking stoves (Still et al. 2011), as confirmed by Dr. Alex Zahnd[1]. Balakrishnan, Mehta, et al. (2014) further endorse the insufficiency of available information required to characterize and evaluate the performance of improved stoves. In combination with inconsistent monitoring and varying maintenance, many ICS programmes are hence claimed to have shown limited success in reducing IAP levels below safe limits (The World Bank 2011).

[1]Dr. Alex Zahnd, International Project Director of the RIDS-Switzerland, and founder of the Smokeless Metal Stove (SMS) successfully implemented in the remote district of Jumla, Nepal. E-mail communication, April 2018.

2.2 Nepal as a country

2.2.1 Geography

Situated in the heart of the Himalayan mountain range, the country of Nepal distinguishes itself by the dramatic nature of varying fashion. The national border stretches out 885 km east-west and 193 km north-south, framing a total land area of 147 181 km^2. Elevations range from 90 m.a.s.l. to 8 848 m.a.s.l.; the altitude of Mount Everest – the highest mountain in the world (Ministry of Health and Population (MOHP), New ERA, and ICF International Inc. 2012). Due to the unique geographical location of the country, Nepal covers three different topographical zones for which the climate changes radically: the flatlands of the Terai in the south, an intermediate hilly zone around the Kathmandu valley and the mountainous region stretched out in the north, characterized by its 8 000 meter peaks (Toffin 1991; Boch-Isaacson and Dobereiner 1987). Elevation range and total land area for each topographical zone is presented in Table 2 (Ministry of Health and Population (MOHP), New ERA, and ICF International Inc. 2012) of which the horizontal stretch is visually displayed in Figure 2.

Table 2: Elevation ranges for Nepal's three topographical zones.

Topographical zone	**Elevation range** / m.a.s.l.	**Area** / km^2
Terai	90 - 1 000	34 019
Hills	610 - 4 876	61 345
Mountains	4 877 - 8 848	51 817

Figure 2: Map of Nepal outlining the different topographical zones.

2.2.2 Climate

There are two main seasons in Nepal. April to September is regarded as summer and October to March considered as winter. The climate is strongly influenced by periods of Monsoon, however the magnitude varies between the different topographical regions (Bodach, Lang, and Hamhaber 2014). V. P. Shrestha (2007) outlines a country specific classification of Nepal's climate zones as five different zones: sub tropical, warm-temperate, cool temperate, alpine and tundra as displayed in Table 3 and 4. In Table 3, elevation ranges and annual precipitation for each topographical zone are presented, summarized from the Nepal Demographic and Health Survey from 2011 (Ministry of Health and Population (MOHP), New ERA, and ICF International Inc. 2012). This in line with Bodach, Lang, and Hamhaber (2014)'s climate analysis of different regions in Nepal, of which mean temperatures for each climate zone are presented in Table 4.

Table 3: Specification of elevation range and annual average precipitation for the five different climate zones in Nepal.

Climate zone	**Elevation range** / m.a.s.l.	**Annual average precipitation** / mm
Sub tropical	$< 1\,200$	100 - 200
Warm temperate	1 200 - 2 400	100 - 200
Cool temperate	2 400 - 3 600	150
Alpine	3 600 - 4 400	25 - 50 in snow
Tundra	$> 4\,400$	Snow

Table 4: Mean temperatures for the five different climate zones in Nepal.

Mean temperatures / ^{o}C		
Climate zone	**Winter**	**Summer**
Sub tropical	15	> 30
Warm temperate	10	24 - 30
Cool temperate	< 5	20
Alpine	< 0	10 - 15
Tundra	< 0	< 0

2.2.3 Demography

According to the latest National Population and Housing Census published in 2011, the population of Nepal was 26.5 million with an annual growth rate of 1.35 % (Central Bureau of Statistics 2012). The distribution of residents varies between the different topographical zones: 7 % live in the mountainous region, 43 % live in the hills and 50 % reside in the flatlands of the Terai. The capital Kathmandu is situated in the hilly zone of which the surrounding district has the highest population density of 4 416 people per square kilometer, as compared to the national overall population density of 180 people per square kilometer. Yet, only 17 % of the population reside in urban areas. The average household size in 2011 was documented to be 4.88, a decrease compared to 5.44 in 2001 (Central Bureau of Statistics 2012). Furthermore, Nepal is divided into five development regions for administrative purposes: Eastern, Central, Western, Mid-Western and Far-eastern. Moreover, the country consists of 75 administrative districts, which in turn are divided into urban municipalities and rural *Village Development Commitees* (VDCs). In 2011, there were 58 municipalities and 3 915 VDCs registered in Nepal (Ministry of Health and Population (MOHP), New ERA, and ICF International Inc. 2012).

Moreover, Nepal is a country characterized by a rich culture due to the large variety of ethnic groups, also called *castes*. In 2011, as much as 125 castes were registered in Nepal, each having their own language and cultural practices (Ministry of Health and Population (MOHP), New ERA, and ICF International Inc. 2012). The most common religions are Hinduism and Buddhism, accounting for 81.3 % and 9.0 % of the total population respectively (Central Bureau of Statistics 2012).

2.2.4 Socio-economic energy situation

Current situation
Nepal is a developing country where the share of biomass in the national energy-mix is ranked to be among the highest in the world, representing 85 % of the total primary energy supply (Malla 2013). Considering the residential sector, around 75 % of the population are dependent on solid biomass fuels for cooking and heating purposes (Central Bureau of Statistics 2012). More than 80 % of the Nepalese population live in rural villages (Central Bureau of Statistics 2012), a sector which stands for 86 % of the national energy demand which mainly consists of wood, crop residues and animal dung (Surendra et al. 2011).

Out of all households in Nepal, firewood is the most common source of energy accounting for 64 % of the total energy consumed to cover daily energy needs (Central Bureau of Statistics 2012). Cleaner fuels such as *Liquid Petroleum Gas* (LPG) is more common in urban areas, however was reported to increase significantly in rural areas as well between 2006 to 2011 (Ministry of Health and Population (MOHP), New ERA, and ICF International Inc. 2012). Hence in a global perspective, Nepal is ranked to be among the countries with the highest level of energy poverty due to the lack of access to modern energy sources and services (Malla 2013).

Future outlook
Malla (2013) performed a study where different energy scenarios were investigated regarding energy access and energy poverty in a future Nepal. It was found that the household sector will continue to account for the largest share of the national energy consumption the coming 30 years for all scenarios, and that four-fifths of the household energy demand would be met by firewood. Thus, the dependence on biomass fuels for cooking and heating purposes is suggested to remain in Nepal the coming decades, and claimed to improve by little unless strong policies are implemented. Furthermore, due to the current lack of a widespread national energy infrastructure, *passive* strategies improving residential comfort are advocated as essential in remote parts of Nepal (Manandhar and Yoon 2015).

Malla (2013) further confirms the correlation between household energy consumption patterns and indoor air pollution levels and highlights the problematic issue of IAP as a strong incentive to eradicate energy poverty in Nepal. Additionally it is suggested that limited efforts on reducing energy poverty risk to cause significant implications on Nepal's social and thereby economic development.

2.3 IAP in Nepal

After an overview of the current IAP situation in the context of Nepal, stove usage characteristics of importance for resulting IAP levels, governmental efforts and alternative intervention strategies are provided in the coming sections.

2.3.1 A severe public health issue

Already in 1986, Reid, Smith, and Sherchand (1986) refers to Nepal as the *"archetypal case of the problems of the biomass fuel cycle in the developing world"* due to the prevalent energy poverty, resulting dependence on firewood and recurring reports on associated exposure to high levels of indoor smoke. As a result, several studies up until today have documented high levels of IAP in Nepalese kitchens generated by indoor burning of solid biomass fuels (Davidson et al. 1986; Reid, Smith, and Sherchand 1986; Dhimal et al. 2016; Parajuli, H. Lee, and K. Shrestha 2016). Moreover, the correlation between elevated IAP levels and health implications has further been established for the specific context of Nepal (Gurung and Bell 2013; Shresta 2004). Joshi, Pandeya, and B. Dhakal (2009) further assessed the prevalence of respiratory infections in a rural hill region for the journal of *Nepal Health Research Council*, and found that respiratory symptoms such as cough, phlegm, breathlessness, wheezing, eye problems, chronic obstructive pulmonary disease (COPD) and bronchial asthma were prominent for high exposures of IAP. This was further confirmed in a study conducted in the Ilam district of eastern Nepal, where it was found that the prevalence of acute respiratory infections (ARI) were higher in households with attachment of black smoke on the kitchen walls (Dhimal et al. 2016), a common scenario particularly in hill and mountainous regions (Ministry of Health and Population (MOHP), New ERA, and ICF International Inc. 2012).

On a national scale, a total number of 7 500 deaths in Nepal were attributed to indoor combustion of solid biomass fuels in 2002 (World Health Organization 2007). Women and children are particularly at risk since women traditionally are responsible for household cooking activities and thus spend more time in the kitchen (Pandey et al. 1985; Joshi, Pandeya, and B. Dhakal 2009), simultaneously carrying around the small children (Dhimal et al. 2016). Ministry of Health and Population (MOHP) in Nepal declares ARIs as a severe public health issue among children under five years of age, being the most common cause of childhood morbidity and mortality (Ministry of Health and Population (MOHP), New ERA, and ICF International Inc. 2012).

Additionally, Pandey et al. (1985) found a correlation between prevalence of declined respiratory function and time spent around the fireplace among Nepalese women of 30 years to 44 years of age, a finding reinforced by the recent study in the Ilam district establishing the interdependence between level of exposure to IAP and decreased lung function (Dhimal et al. 2016).

Moreover, the magnitude of IAP levels has been found to vary between different topographical zones in Nepal, being more severe in rural and hilly areas than urban flatlands (I. L. Shrestha and S. L. Shrestha 2005). Coincidentally, children in the Western development region and hilly zone have been declared to be particularly prone to acquire symptoms of ARIs (Ministry of Health and Population (MOHP), New ERA, and ICF International Inc. 2012).

2.3.2 Stove usage practices

The most common types of biomass stoves used in Nepal today are referred to as *Traditional Cooking Stoves* (TCS) and *Improved Cooking Stoves* (ICS) (Dhimal et al. 2016). Despite the lack of consistent definitions of these stove types (The World Bank 2011), a typology clarification of general stove characteristics is presented below.

Traditional cooking stove (TCS)

An open fire or a simple cooking stove made by household members or local artisans, often lacking design considerations for energy efficiency or smoke exhaust systems such as chimneys or vents (Fuller, Zahnd, and Thakuri 2009).

Improved cooking stove (ICS)

Today there is no universal definition of an ICS considering technical standards of performance. The improved features are relative to the type of traditional stove considered and reflects the aim of the design improvement (The World Bank 2011). However, an ICS is generally referred to as a biomass-fired stove where the improved characteristics are intended to increase thermal efficiency (i.e higher percentage of energy from fuel absorbed by the pots) (The World Bank 2014). The thermal efficiency is however the product of an increased heat transfer efficiency (i.e. how much of the heat generated that is absorbed by the pot) and combustion efficiency (i.e how much of the energy from the fuel that is converted to heat and radiant energy), where the latter determines the rate at which pollutants are generated. Moreover, these internal efficiencies are dependent on different design parameters. Stoves with high heat transfer efficiencies have been reported to decrease the combustion efficiency, resulting in an increase of pollutant emissions

(Jetter et al. 2012). Thus, the nature of the improved design is declared as vital to consider when evaluating the performance of an ICS when it comes to reducing IAP levels (The World Bank 2014). Moreover, stoves fitted with smoke exhaust systems such as fans or chimneys are additional features which falls within the category of improved cooking stoves (The World Bank 2011).

2.3.3 Interventions

Indoor air quality (IAQ) in kitchens of the developing world depends on several parameters, among which stove type, quality of fuel and ventilation situation are crucial (Parajuli, H. Lee, and K. Shrestha 2016). Thus, interventions can be employed either at the source of pollution by switching to cleaner stoves and fuels or in the living environment by ensuring sufficient ventilation in order to reduce smoke accumulation (Goldemberg 2000; World Health Organization 2000).

Governmental action

Intervening at the source of pollution
The Nepalese government has taken action by committing to the UN *Sustainable Energy for All by 2030* initiative (Malla 2013). A target of providing *Clean Cooking Solutions for All 2022* has thus been set up and subsidies for distribution of improved cooking stoves have been implemented and executed by the governmental agency of *Alternative Energy Promotion Center* (AEPC) (Singh et al. 2012; Nepal Energy Efficiency Programme (NEEP) 2011), in which international organizations also are involved (Nepal Alliance for Clean Cookstoves (NACC) 2017). Only inhabited regions above 2 000 meters of altitude are eligible for governmental subsidies of 4 000 Nepali Rupees per family to install an improved metallic cooking stove (Nepal Energy Efficiency Programme (NEEP) 2011). In 2013, the *National Alliance of Clean Cookstoves* (NACC) was formed by organizations involved in clean cooking technologies and is intended to coordinate efforts of different stakeholders on promoting clean cooking solutions (Nepal Alliance for Clean Cookstoves (NACC) 2017).

ICS distribution programmes are however reported to have had limited success in Nepal (Malla 2013). Comparative studies have shown that despite a substantial reduction in smoke accumulation, indoor concentrations of IAP still risk to exceed permissible values for safe health (Parajuli, H. Lee, and K. Shrestha 2016; Singh et al. 2012; Reid, Smith, and Sherchand 1986). It is further acknowledged that the performance of an ICS in field deviates from the the simulated performance during laboratory conditions (Nepal Energy Efficiency Programme (NEEP) 2011; Jetter et al. 2012). Insufficient maintenance and lack of training on proper operation are factors suggested to result in elevated levels of IAP in Nepalese kitchens even with an ICS[2]. In addition, physical breakage of prefabricated models due to complicated transportation to remote areas in mountainous regions in Nepal has further been reported as an obstacle in the achievements of ICS distribution programmes (Nepal Energy Efficiency Programme (NEEP) 2011).

Role of natural ventilation

Intervening in the living environment
Given the prevalent energy poverty and predictions on a continued dependence on solid biomass, intervening in the living environment in terms of improving the ventilation situation has been declared as a cost efficient and rapidly employable measure on reducing exposure indoor air pollutants required at present (Cowlin 2005; Parajuli, H. Lee, and K. Shrestha 2016). Passive ventilation strategies, i.e. increasing ventilation rates by taking advantage of natural driving forces are crucial since energy intensive ventilation solutions are neither supported by poor rural households nor the non-existing energy infrastructure in remote areas of Nepal. Parajuli, H. Lee, and K. Shrestha (2016) and Cowlin (2005) further stress that increasing natural ventilation is as important as using cleaner stoves and fuels in ensuring a healthy indoor air quality. This since IAP levels risk to accumulate to health deteriorating levels despite cooking on relatively clean stoves if ventilation rates are low (Cowlin 2005; Singh et al. 2012).

The correlation between ill ventilated kitchens and health impacts has further been established by B. Thapa and Chaurasia (2014) who found that the prevalence of respiratory diseases were more common in Nepalese households with inadequate ventilation. As a result, Parajuli, H. Lee, and K. Shrestha (2016) highlight the importance of reducing IAP levels by natural ventilation in rural, mountainous households specifically due to the debatable performance of ICS in ensuring IAP levels below safe limits.

[2]Dr. Alex Zahnd, International Project Director of the RIDS-Switzerland and founder of the Smokeless Metal Stove (SMS) successfully implemented in the remote district of Jumla, Nepal. E-mail communication, April 2018.

2.4 Nepalese domestic habitat

Depending on geographical location in Nepal, the use of materials, tools, building traditions, indoor plans as well as usage of the residential unit varies (Toffin 1991). A background assessing distinctive traits of the Nepalese domestic habitat of high altitude settlements will follow, highlighting features of relevance considering thermal comfort and ventilation prerequisites including both architectural constraints as well as cultural practices.

2.4.1 Vernacular architecture

Vernacular architecture is defined as the architectonic features of a building resulting from the use of local materials and building practices, reflecting the aim to provide a shelter from the surrounding environment (Bodach, Lang, and Hamhaber 2014). The energy poverty in Nepal hence makes it crucial for houses in mountainous regions of colder climates to maintain an acceptable indoor thermal comfort with least energy input possible. The concept of *bioclimatic design* comprise passive solutions where architectonic features of a building reflects a response to provide a comfortable indoor environment considering the local climate; a result of *climate responsive* design techniques (Bodach, Lang, and Hamhaber 2014).

Bodach, Lang, and Hamhaber (2014) present an extensive study of climate responsive design strategies in Nepalese vernacular architecture for all climate zones. As the focus in this study is to investigate factors influencing thermal comfort in high altitude areas, a brief overview of architectonic features suggested for *cool temperate* as well as *alpine* climates is provided in the following sections.

Bioclimatic design strategies for cool temperate climates

Nepalese regions with a cool temperate climate (2 200 m.a.s.l. − 3 300 m.a.s.l.) are exposed to a strong insolation throughout the whole year. An optimized climate responsive design should thus include considerations for passive and solar heating in winter as well as to ensure sufficient ventilation during summer in order to avoid overheating.

A high thermal mass in the foundation and structure of the house is hence declared as desirable in order to profit from the time lag of the release of heat absorbed by the building during sunny winter days. Additionally, a compact settlement layout reducing the heating volume in winter as well as medium sized windows allowing for adequate ventilation in summer are suggested to provide comfortable indoor environments in cool temperate climates (Bodach, Lang, and Hamhaber 2014). Active solar or conventional heating is however presented as necessary during half of the year to maintain acceptable indoor comfort levels during colder seasons.

Bioclimatic design strategies for alpine climates

The alpine climate zone of Nepal (3 300 m.a.s.l. – 5 000 m.a.s.l.) is colder and dryer than cool temperate regions. Nonetheless, high altitude alpine provinces still profit from strong insolation both summer and winter. Making use of passive and active solar heating is hence presented as essential, particularly during the colder winter months.

Suggested climate responsive design features of vernacular architecture are thus focused on amplifying the passive solar heating effect. House foundations and building envelopes with thick walls and a high thermal mass are presented as required to cope with the more extreme diurnal temperature differences. Small sized openings (10 % – 15 % of the wall) are further recommended to limit heat losses. As for cool temperate climates, limiting the heating volume by a compact building layout is desirable. An additional heating source is however considered necessary throughout the longer periods of very low ambient temperatures.

2.4.2 Cultural influence

Nepalese vernacular architecture is claimed to be strongly influenced by cultural ethnicity (Bodach, Lang, and Hamhaber 2014; Toffin 1991). The inhabitants of the different topographical zones in Nepal diverge in cultural entity, linguistic family as well as physical features. As a result, the difference in topography has been observed to be closely linked to local culture and religion which in turn is shown to have a large influence on local building practices and architectonic expression (Toffin 1991). The common denominator is however that the appearance and arrangement of the domestic habitat is considered as important as a palace or a temple. Thus, the spatial planning and decorations are highly influenced by religious beliefs. In some cases it is even argued that cultural differences are as influential as ecological layer (i.e. characteristics of the surrounding environment) considering local architectonic specificity since cultural building practices migrates with the people. As an example, similar housing structures can be found in the Terai as well as in the hilly regions where the *Newar* cast resides. From a sociological perspective, the residential unit is considered as a symbol of a given social and political organization (Toffin 1991).

2.4.3 The role of cooking stoves and kitchens

Independent of ethnic heritage and geographic location, the fireplace or cooking stove has a central role in the Nepalese domestic habitat being a social center. Cooking is a ritual act in the Nepalese culture where the stove serves as an indispensable gathering point in the domestic habitat (Toffin 1991). If cooking over open fire, the meals are most commonly taken around the fireplace where the seating is determined by a specific ranking of the family and guests. Furthermore, lighting the stove or an open fire is the only available source of additional heat in rural Nepal due to the prevalent energy poverty. As a result, rural households are reported to have the stove lit more frequently since stove usage practices also include heating the home, especially in the hills and mountainous regions (Malla 2013). Thus, the colder climate, the more time is spent in the kitchen being the only comfortable place to be at night (H. B. Rijal and Yoshida 2006; Bodach, Lang, and Hamhaber 2014). Kitchens are therefore often used as multipurpose rooms where residents eat, work, relax and sleep. In some traditions it is common for particularly children to sleep around the fireplace (Toffin 1991).

2.4.4 Indoor thermal environment

As briefly mentioned in the introduction, residents in the Himalayan region are reported to live far below universal comfort standards (H. B. Rijal and Yoshida 2006). This was further confirmed by Fuller, Zahnd, and Thakuri (2009)'s findings on indoor temperatures in the Humla province, highlighting that comfort levels in Nepalese high altitude settlements are considerably lower than what *"internationally is recognized as acceptable"*.

Nonetheless, Nepalese people living at high altitudes are claimed to adapt well to the surrounding climate resulting in a wide comfort zone. A series of studies on thermal comfort in Nepalese households performed by H. B. Rijal and Yoshida (2006) and H. Rijal, Yoshida, and Umemiya (2010) indicate that the perception of the *neutral temperature*, a term referred to as the globe temperature at which respondents express a *neutral* thermal sensation (i.e not feeling too warm or too cold), was significantly lower for high altitude regions (10.7 ^{o}C) (H. B. Rijal and Yoshida 2006). If globe temperatures were high, neutral temperatures were also found high (H. B. Rijal and Yoshida 2006). Thus, the neutral temperature is suggested to be directly proportional to the surrounding thermal environment, indicating that Himalayan residents are accustomed to cope with fluctuating indoor temperatures (H. B. Rijal and Yoshida 2006; H. Rijal, Yoshida, and Umemiya 2010).

Nevertheless, despite various adaptation measures and wide comfort zones, respondents in a survey on winter thermal comfort in a high altitude region expressed the desire to improve indoor thermal comfort (H. B. Rijal and Yoshida 2006).

2.4.5 Ventilation situation specification

The general ventilation situation in kitchens using biomass for cooking and heating in developing countries has been stated by several studies as insufficient with respect to indoor accumulation of health deteriorating IAP (Goldemberg 2000; Pokhrel et al. 2015; Rehfuess 2006). Considering the physical prerequisites of Nepalese vernacular architecture to employ natural ventilation, Toffin (1991)'s observations confirm the climate responsive opening designs suggested by Bodach, Lang, and Hamhaber (2014) on modestly sized windows in high altitude regions. Here it is further claimed that openings are designed to permit minimum light to enter in order to minimize the heat losses in settlements situated in harsh climate conditions (Toffin 1991). A small hole in the wall or in the ceiling intended to reduce smoke accumulation during stove usage activity is sometimes present. These ventilation units are however described as deficient in letting enough smoke escape in order not to pollute the indoor air to the risk of being hazardous to inhale (Toffin 1991).

Moreover, Dhimal et al. (2016) highlight the importance of architectonic prerequisites allowing for sufficient ventilation by calling for the employment of governmental standards on adequate opening sizes in house constructions as the number one recommendation on how to limit IAP related health impacts in biomass-reliant households.

2.5 Case study: Chame, Manang

2.5.1 Criteria of site of study

The research questions in this thesis were to be answered by a case study of which the criteria regarding choice of location were formulated as follows:

1. **High altitude settlement situated in the hilly or mountainous topographical zone.** The complex issue of maintaining a comfortable indoor environment by using a biomass-fired cooking stove for heating purposes which simultaneously generates health hazardous pollutants is of particular interest in high altitude regions with cold climatic conditions.

2. **Rural area.** Since the scope of this study includes an assessment of IAP resulting from stove usage, households dependent on solid biomass to cover daily energy needs was a main criteria for the site of study. The majority of rural areas in Nepal are stated to be reliant on solid biomass fuels due to the prevalent energy poverty (Surendra et al. 2011).

2.5.2 Selection of site of study

The village of Chame, headquarters of the Manang district in the north-central part of Nepal was chosen as site of study. Situated on 2 650 meters of altitude, Chame is classified as a village in the cool temperate climate as presented in Table 3 in Chapter 2. Until 2015, Chame was only to be reached by foot (S. Lee 2015). Now a winding motorable road connects Chame to the national road network, making it possible to reach Besisahar in 10 hours. According to the latest National Population and Housing Census report performed by the Central Bureau of Statistics (CBS) in 2011, the population in Chame was assessed to 1 129 inhabitants. In addition, out of a total number of 279 households, 274 households (98 %) were documented to be reliant on firewood. The remaining 5 households were recorded to be using gas (Central Bureau of Statistics 2014).

Chame is situated in the heart of the Annapurna mountain range which due to its unique nature, biological and cultural diversity constitutes the core in the largest protected area of Nepal called the *Annapurna Conservation Area*. The "Annapurnas" is the most popular trekking destination in Nepal attracting around 60 % of the country's total trekking tourists which provides economic benefits to the area but have also resulted in severe environmental impacts (Natural Trust for Nature Conservation 2018b). High rates of tourism increase the firewood consumption for cooking and heating which accelerates the ongoing deforestation and the extensive waste disposal poses a major threat in this unique nature reserve. Thus, an integrated conservation and development program has been developed under the *Annapurna Conservation Area Project* (ACAP) which main objectives are stated as follows (Natural Trust for Nature Conservation 2018b):

- Conserve the natural resources for present and future generations
- Promote sustainable social and economic development for local people
- Develop tourism which minimizes negative impacts on socio-cultural as well as economic environments

As a result, an *Alternative Energy Program* (AE) has been created under the ACAP organization in order to reduce dependence on firewood by both promoting fuel efficient energy devices through the introduction of improved cooking stoves (ICS) as well as alternative energy sources such as gas and solar heaters (Natural Trust for Nature Conservation 2018a).

(a) (b)

Figure 3: Pictures taken in Chame, November 2017.

3 THEORY

The following chapter presents the theoretical background upon which the research methods applied are based. As a result, the general research approach for some of the research questions are already announced in this chapter, before being thoroughly described in the coming chapters outlining the research strategy in more detail.

3.1 Passive ventilation

Passive ventilation refers to the natural airflow through a building which is driven by natural forces induced by pressure differences between indoor and outdoor air (Chartier and Pessoa-Silva 2009). Two types of passive airflow can occur through a building which Breen et al. (2014) further defines as:

- **Leakage:**
  Unintentional airflow through gaps or cracks in the building envelope (also described as *infiltration* and *exfiltration*).

- **Natural ventilation:**
  Intentional and controlled airflow by actively opening and closing openings such as windows and doors.

Leakage and natural ventilation is driven by two main natural forces: stack effect and wind effect (Breen et al. 2014; Chartier and Pessoa-Silva 2009). The stack effect refers to pressure differences resulting from differences in temperature between indoor and outdoor air (European Committee for Standardization 2017). Wind effect induced airflow result from pressure differences caused by wind forces on the building envelope, generating a positive pressure on the wind ward side of a building and a negative pressure on the lee ward side as depicted in Figure 5 (Chartier and Pessoa-Silva 2009).

The respective influence of stack effect and wind effect on the resulting airflow rates depends on climatic conditions as well as opening configuration, i.e. how the openings are placed relative each other. When openings are situated on the same side of the building, i.e. *single sided ventilation*, the stack effect is dominant. In contrast, when openings are placed on opposite sides of the building, i.e *cross ventilation*, the wind effect is the major driver of the airflow through the building (Chartier and Pessoa-Silva 2009). When it comes to unintentional air leakage, the influence of wind on the building envelope is claimed to have been debatable in literature. However there are studies indicating that wind speed and wind direction do have an influence on the magnitude of the resulting leakage as well (Chartier and Pessoa-Silva 2009).

Modified illustrations from Chartier and Pessoa-Silva (2009) of natural induced airflow through buildings with single sided as well as cross ventilation are presented in Figure 4 and 5 respectively.

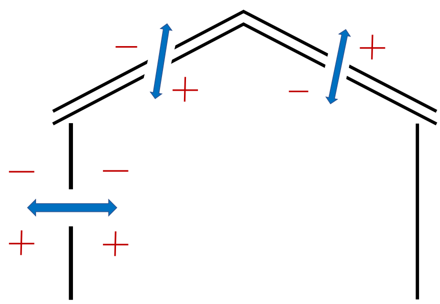

Figure 4: Stack-effect induced airflow resulting from temperature differences in a building with single sided ventilation. Positive and negative pressures resulting from high and low temperatures are depicted as plus and minus signs respectively. Resulting airflow directions through openings and/or cracks in walls and roof are displayed as blue arrows.

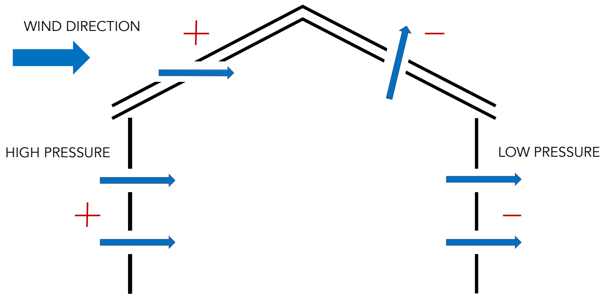

Figure 5: Wind-induced pressure differences on a building envelope with cross ventilating windows. Positive and negative pressures are depicted as plus and minus signs respectively. Resulting airflow directions through openings and/or cracks in walls and roof are displayed as blue arrows.

3.2 Assessing IAP

Assessing indoor levels of stove generated pollutants resulting from indoor burning of solid biomass has previously been conducted by actual field measurements, computer simulations or by simple mathematical models (Johnson, Edwards, et al. 2014; Edwards et al. 2014). Field measurements are expensive and requires extensive equipment and expertise but provides important qualitative information on the actual situation regarding IAP levels for specific households (World Health Organization 2000; Shresta 2004). Both complex computer based programs and simple mathematical models are recognized as valid alternatives in providing indicative pollutant concentration levels resulting from specific stove and fuel combinations (World Health Organization 2015; Johnson, Edwards, et al. 2014). Computer based simulation tools such as computational fluid dynamics (CFD) and empirical measurements are however used complementary, in order to validate the computational model before proceeding with further analysis of fictive scenarios (Sapkota, Uprety, and Gokhale 2015). This since CFD calculations require thorough details on room characteristics as well as the source of emission (Johnson, Edwards, et al. 2014). Simplified mathematical models such as the *single zone model* have thus been widely adopted the last 30 years in assessing household energy related air pollution due to the advantageous trade-off between simplicity and accuracy with respect to the assumptions used (World Health Organization 2015).

A calculation approach in form of a simplified single zone model was considered suitable in this study, given the limited time and resources not allowing for conducting field measurements also required for verifying complex computational models. Additionally, single zone model calculations have previously been applied to estimate indoor concentrations of stove generated pollutants with respect to WHO Indoor Air Quality (IAQ) guidelines (Johnson, Lam, et al. 2011; Ruiz and Masera 2018). Furthermore, a mathematical approach is convenient when aiming to evaluate and compare the performance of hypothetical improvements which is the main focus in the scope of this study. In the following subsections, a brief description of the single zone model and the theory behind the required input parameters are provided.

3.2.1 Single zone model

The single zone model is based on the assumption of perfect mixing, i.e. that pollutant emissions are homogeneously distributed in space (Johnson, Lam, et al. 2011). Resulting IAP concentrations are thus dependent on room volume, air exchange rates as well as duration of stove usage and stove related pollutant emission rates (World Health Organization 2015; Johnson, Lam, et al. 2011; Johnson, Edwards, et al. 2014). Key input parameters are elaborated below.

3.2.2 Air exchange rate (AER)

Air exchange rate (AER) is defined as the rate at which indoor air is exchanged with outdoor air hence is a critical aspect in air pollution exposure assessments (Breen et al. 2014). There are two main types of models for assessing AER: empirical models and physical models. Empirical models are based on existing measurements reported in AER databases collected from various field studies of different geographical regions, season and building characteristics. Physical models are based on case-specific fundamental theory. More information about the different models can be found in Chartier and Pessoa-Silva (2009).

The AER per second of a room with a given volume can be calculated as follows (Breen et al. 2014):

$$AER = \frac{Q}{V} \tag{1}$$

where Q is the airflow rate in and out of the room measured in $m^3 \cdot s^{-1}$ and V is the room volume measured in m^3. Temporal variations in AER resulting from leakage and natural ventilation are dependent on local weather conditions such as ambient temperatures and wind characteristics as well as on occupancy behavior considering the practice of opening openings (Breen et al. 2014). As a result, AER based exposure assessments made on both individual and community level can be based on information derived from questionnaires or residential surveys as well as on public property assessment databases (Breen et al. 2014).

3.2.3 Emission factors

Pollutant emissions from stove usage is the determinant factor of the indoor air quality (IAQ) in households reliant on solid biomass fuels (Johnson, Edwards, et al. 2014). The standard measure of pollutants generated in a combustion process is the *emission factor* (E_f), defined as the mass pollutant emitted per unit mass of fuel consumed (g/kg fuel) of which the magnitude is determined by fuel type and stove efficiency (Bhattacharya, Albina, and Salam 2002).

As briefly mentioned in the background, the term *stove efficiency* is usually referred to as the overall thermal efficiency (OTE), defined as the ratio of energy delivered for cooking purposes to the total energy content in the fuel. OTE is the product of combustion efficiency (CE) and heat transfer efficiency (HTE) as displayed in Equation 2 (Jetter et al. 2012):

$$OTE = CE \cdot HTE \tag{2}$$

where CE is the fraction of energy released by combustion to the energy content in the fuel (i.e. how well the fuel is combusted) and HTE is the fraction of the released energy that is absorbed by the pot during cooking (Jetter et al. 2012). A high OTE can thus be achieved by increasing either CE or HTE. Emission factors are however a direct result of CE, as the generation of toxic compounds originates from an incomplete combustion of the fuel, referred to as *Products of*

Incomplete Combustion (PICs) (Edwards et al. 2014). Small differences in CE have the potential to have a large impact on pollutant emissions (Jetter et al. 2012).

A 100 % complete combustion process would only generate products of water vapor and non-toxic carbon dioxide (CO_2). CE can in general terms hence be described as the ratio of emitted CO_2 to the total emitted carbon (Jetter et al. 2012). Since carbon monoxide (CO) represents the largest mass of the PICs resulting from incomplete combustion of solid biomass, the definition of CE can be modified (MCE) and approximated on a carbon-molar basis as described by Equation 3 (Edwards et al. 2014; Jetter et al. 2012):

$$MCE = \frac{CO_2}{CO_2 \ + \ CO} \tag{3}$$

where MCE signifies the modified combustion efficiency. However, MCE is not only a function of stove *or* fuel type. Resulting emissions are rather determined by the stove and fuel *combination*, of which fuel quality (e.g. humidity content) and the way the stove is operated both have a significant impact (Edwards et al. 2014).

3.2.4 Emission rates

The *emission rate* (E_r) is defined as the rate at which pollutants are generated in the stove. In single zone models, the simplest E_r function assumes a constant emission rate (Johnson, Edwards, et al. 2014) and can be assessed in mass per time unit (g/s) as presented in Equation 4:

$$E_r = F \cdot E_f \tag{4}$$

where F is the fuel burning rate in kg/s and E_f the pollutant emission factor in g/kg fuel. The fraction of pollutants reaching the indoor environment is however dependent on the physical characteristics of the stove. Enclosed combustion chambers and smoke exhaust systems such as chimneys or vents both reduce the risk for accumulation of IAP. User behavior further influences the level of emissions reaching the kitchen in terms of how well pots are fitted to the stove and the method of refueling (Edwards et al. 2014; Johnson, Edwards, et al. 2014). Open fires or traditional stoves are not provided with any ventilation systems thus the fraction of stove correlated emissions entering the room has in previous IAP assessments been assessed to one (Johnson, Lam, et al. 2011). However, even stoves with chimneys can generate pollutants into the indoor environment by so called *fugitive emissions*, i.e. unintended smoke leakage from the stove and from joints on the chimney pipe (Jetter et al. 2012). The magnitude of the overall fugitive emissions is however highly case specific and dependent on stove quality as well as frequency of maintenance (Reid, Smith, and Sherchand 1986).

3.2.5 Stove characteristics influencing IAP

To sum up, E_f, E_r, F and the level of fugitive emissions (i.e. fraction of pollutants generated in the stove reaching the indoor environment) all have an impact on IAP concentrations hence become important parameters to consider in IAP assessments. E_f is a function of the stove and fuel type combination. E_r is dependent on the rate at which the fuel is consumed (F) which in turn is determined by both stove type and fuel quality. The level of fugitive emissions is attributed to the physical features of the stove as well as user behavior. As a result, the two coming sections highlight stove related characteristics important to consider in IAP assessments based on simulations where legit input parameters are required for valid results.

ICS: Efficiency and emission rates

Aprovecho Research Center conducted a survey for the *U.S Environmental Protection Agency* where fuel use and emission rates for fifty cooking stoves were tested in laboratory settings (Still et al. 2011). It was found that some improved cooking stoves have larger emission factors (E_f) of CO and $PM_{2.5}$ than open fires due to that the improved features not necessarily address combustion efficiency. Even if the amount of useful heat for cooking is increased, products of incomplete combustion are still there (Parajuli, H. Lee, and K. Shrestha 2016). Dr. Kirk Smith further reinforce the importance of understanding that an increase of HTE which slightly improves OTE might result in two to three times more pollution generated per meal (Still et al. 2011). Additionally, Zhang et al. (1999b) confirm that improved stoves often increase HTE but decrease combustion efficiency, resulting in higher fuel consumption and a larger generation of PICs (Zhang et al. 1999a). It has thus been suggested that efficient stoves are often unclean and clean stoves are often inefficient in terms of fuel use (Parajuli, H. Lee, and K. Shrestha 2016). There are however ICS designs intended to increase combustion efficiency aiming to reduce the generation of PICs (Singh et al. 2012). As a result, due that the improved features of an ICS can be of varying nature, different ICS have different potentials to reduce IAP levels (Ramakrishna, Durgaprasad, and Smith 1989).

Chimney: Indoor emission reduction potential

The purpose of a chimney is to channel out the smoke from the combustion chamber of the stove to avoid indoor smoke accumulation (Kshirsagar and Kalamkar 2014). In addition, a chimney allows for a more rapid air movement through the stove which theoretically enhances combustion efficiency. However, the heat transfer efficiency risk to be compromised by elevated airflow rates, resulting in a prolonged duration of cooking activity in turn increasing fuel consumption per cooking task. As a result, there is an optimum temperature for a chimney (120 ^{o}C) in order to ensure complete combustion and to maximize heat utilization efficiency (Thakuri S. 2006). A chimney however requires continuous maintenance such as removal of soot to avoid chimney clogging. This in order to sustain a sufficient draft to reduce IAP levels by limiting the generation of PICs as well as venting out the stove generated smoke (Kshirsagar and Kalamkar 2014). As mentioned above, leakage from joints in the chimney pipe is another factor of importance contributing to chimney specific fugitive emissions (Nepal Energy Efficiency Programme (NEEP) 2011).

There is no consensus in literature on a general fugitive emission reduction factor (i.e. the reduction of stove generated pollutants reaching the indoor environment) for neither chimneys per sé nor stoves fitted with chimneys used in field (Ramakrishna, Durgaprasad, and Smith 1989). A well functioning chimney has been documented to reduce indoor concentrations of CO by 90 % (Smith et al. 2010) and laboratory tests claim that a chimney has the potential of reducing IAP levels by 99 % (Still et al. 2011). Yet, fugitive emissions of 1 % – 50 % were attributed to chimney stoves in the development of IAQ emission rate guidelines provided by WHO, based on findings in a RESPIRE study in Guatemala and an ICS project in Mexico (Johnson, Edwards, et al. 2014). Moreover, J. Kandpal, Maheshwari, and T. Kandpal (1994) found that indoor concentrations of CO were reduced by 50 % − 60 % when comparing measurements from an ICS fitted with chimney and a traditional stove in India. In the context of Nepal, a study comparing an ICS with a TCS in rural mountainous households found a reduction of around 30 % on indoor CO levels, still exceeding permissible concentrations for safe health (Parajuli, H. Lee, and K. Shrestha 2016). Furthermore, AEPC declares emission reduction factors for an ICS with chimney to range between 30 % − 90 %, as further confirmed by M. Thapa and Subba (2015).

Given that both the improved features of an ICS as well as the presence of a chimney affect IAP levels, data on the relative reduction in accumulation of toxic pollutants allocated to either combustion efficiency or smoke exhaust system is hard to find. A summary of the *combined* chimney stove reduction potentials found in literature is thus presented in Table 5.

Table 5: Emission reduction potentials for chimney stoves reported in literature with respect to the performance in reducing indoor concentrations of carbon monoxide (CO).

Chimney stove CO reduction potential		
Source	**Field / Laboratory**	**CO reduction**
Still et al. (2011)	Lab	99 %
Smith et al. (2010)	Field	90 %
Johnson, Edwards, et al. (2014)	Field	49 % - 99 %
Reid, Smith, and Sherchand (1986)	Field	78 %
Singh et al. (2012)	Field	60 %
AEPC	Lab	30 % - 90 %
Parajuli, H. Lee, and K. Shrestha (2016)	Field	17 % - 30 %

Laboratory tests on stove performance are however acknowledged to deviate from the practical use in field. Resulting indoor concentrations of IAP is largely dependent on occupant behavior, which is not accounted for in controlled laboratory settings (Edwards et al. 2014). As a result, Reid, Smith, and Sherchand (1986) states that to accurately determine improvements in stove efficiency and indoor smoke accumulation, field measurements are needed.

3.3 Indoor Air Quality (IAQ)

3.3.1 WHO guidelines and limit values

Why guidelines?

World Health Organization (WHO) has developed guideline values on indoor concentrations for several indoor air pollutants in order to protect public health since *indoor air quality* (IAQ) is a concern both in industrial as well as in developing countries (World Health Organization 2010). IAQ guidelines are targeted to professionals, specialists and authorities who are involved in preventing health risks from environmental exposures as well as in the design and use of buildings. The guideline values are based on evidence including an aggregate evaluation of indoor sources, current indoor and outdoor concentrations, their interdependence as well as health effects resulting from pollutant specific kinetics and metabolism (World Health Organization 2010). In the report *WHO Guidelines for Indoor Air Quality: Selected Pollutants* published in 2010, the main goal with developing IAQ guidelines is declared as follows:

"The primary aim with these guidelines is to provide a uniform basis for the protection of public health from adverse effects of indoor exposure to air pollution, and to eliminate or reduce to a minimum exposure to those pollutants that are known or are likely to be hazardous." (World Health Organization 2010)

Focus on household fuel combustion

Based on the previous IAQ guidelines *Selected Pollutants*, WHO has developed special guidelines for indoor air pollutants correlated to household fuel combustion (World Health Organization 2015). This documentation comprise both a summary of specific pollutant guideline values as well as recommendations on interventions intended to serve as an informative base for policy makers, the health sector and technical staff when developing IAP intervention strategies, and to highlight the associated health development benefits with eradicating the current global energy poverty inequalities (World Health Organization 2015).

Indicator pollutants

Particulate matter with a diameter of less than 2.5 μm in diameter ($PM_{2.5}$) and carbon monoxide (CO) are the two most important health hazardous products of incomplete combustion (World Health Organization 2015). Indoor burning of solid biomass is associated with high indoor concentrations of these pollutants. Hence, $PM_{2.5}$ and CO are considered as important indicators of health deteriorating IAP originating from household energy use. Table 6 displays IAQ guideline values on indoor concentrations of $PM_{2.5}$ and CO to ensure safe health, as presented by World Health Organization (2015).

Table 6: WHO Indoor Air Quality (IAQ) guideline values for indoor concentrations of $PM_{2.5}$ and CO.

Mean concentration over averaging time				
Pollutant	**15 min**	**1 h**	**8 h**	**24 h**
$PM_{2.5}$ / (μg · m^{-3})	-	-	-	25
CO / (mg · m^{-3})	100	35	10	7

The presented guidelines are based on recent evidence on fuel use, resulting emissions and correlated health risks and are stated to ensure "*no or minimal risk for adverse health outcomes*" with a "*high quality*" level of evidence. Details of where to find more information about the development of these guidelines can be found in the full document *WHO guidelines for indoor air quality: household fuel combustion* (World Health Organization 2015).

3.3.2 Nepalese standard

In 2009 the Government of Nepal published a *National Indoor Air Quality Standard* with respect to $PM_{2.5}$ and CO. The aim with the standard is to provide guidance for improving public health and maintaining a balance between energy savings, climate change and indoor environment. Nepalese guideline values on indoor concentrations of $PM_{2.5}$ and CO are presented in Table 7 (Ministry of Environment and Technology 2009):

Table 7: National IAQ guidelines for indoor concentrations of $PM_{2.5}$ and CO formulated by the Nepalese Government.

Mean concentration over averaging time				
Pollutant	**15 min**	**1 h**	**8 h**	**24 h**
$PM_{2.5}$ / (μg · m^{-3})	-	100	-	60
CO / (mg · m^{-3})	-	40	10	-

3.3.3 Carbon monoxide as an indicator

Both $PM_{2.5}$ and CO are frequently used as indicator pollutants for cookstove emissions due to their abundance and relative simplicity to measure (Jetter et al. 2012). Yet, CO is the most abundant product of incomplete combustion and is easier to measure than $PM_{2.5}$ (Smith et al. 2010; Still et al. 2011). Moreover, the inter-correlation between concentrations of $PM_{2.5}$ and CO resulting from stove usage activity has been empirically established (Parajuli, H. Lee, and K. Shrestha 2016; Singh et al. 2012), even if this correlation has not been attributed to all stove types (Still et al. 2011). Additionally, Smith et al. (2010) further suggest CO to be a *"reliable surrogate for fine particles"*. As a result, epidemiological field studies aiming to estimate indoor levels of health hazardous pollutants have focused on CO concentrations only (Smith et al. 2010). Also simulation based studies investigating exposure potentials of biomass fired cooking stoves in hypothetical kitchens have used CO as an indicator pollutant (Zhang et al. 1999b).

Specific toxicity

Not only does CO serve as an indicator of elevated levels of other toxic substances, exposure to CO is health hazardous per sé (Oluwole et al. 2012). Due to that CO has an affinity to bind to the carrier protein hemoglobine 200 times to 250 times greater than oxygen, exposure to CO impairs the transport of oxygen in the body resulting in oxygen deficiency and tissue damage of organs (Oluwole et al. 2012). Thus, pregnant women are particularly vulnerable since a fluctuating oxygen supply to fetuses risk to cause adverse pregnancy outcomes (Balakrishnan, Ramaswamy, and Sankar 2004).

3.4 Thermal comfort

3.4.1 Definition

Thermal comfort in buildings is a subjective measure on how the indoor climate is perceived by the occupant with respect to the surrounding thermal conditions. More specifically, the ASHRAE standard 55 of *Thermal Environmental Conditions for Human Occupancy* defines thermal comfort as:

"That condition of mind which expresses satisfaction with the thermal environment."

The perception of thermal comfort is dependent on the *human thermal sensation*, i.e. the overall thermal balance of the body of a human being, which is affected by several factors (Parsons 2003; ISO 2005). The concept of thermal comfort is not entirely a physiological phenomenon, psychological aspects are also influential. The reason to the subjectivity of thermal sensation is not known, yet the impacts of feeling uncomfortable due to the surrounding climate (i.e. being too hot or too cold) range from temporary discomfort to implications on health and well-being (Parsons 2003). The interest in assessing thermal comfort is however not to understand what causes this subjectivity, rather to present required conditions for creating thermally comfortable environments (Parsons 2003).

There are several standards on how to assess and measure thermal comfort, of which more information can be found in Deliahmedova (2016). In 1970, Fanger developed a formula including six fundamental parameters affecting thermal sensation, upon which theoretical comfort assessments as well as the internationally recognized comfort standards are based. These comprise environmental parameters such as air temperature (T_a), mean radiant temperature (MRT), air velocity (v_a), relative humidity (RH), as well as occupancy behavior considering clothing and activity level (Parsons 2003).

3.4.2 ISO standard

International Organization for Standardization (ISO) developed the standard ISO 7730 to present methods of predictions and evaluations of thermal environments to which human beings are exposed (ISO 2005). Here thermal comfort is assessed by applying the *Predicted Mean Vote* (PMV) model, including indices on *Percentage of People Satisfied* (PPD). The parameters formulated by Fanger are inserted in specific equations resulting in a number which is evaluated according to a seven step thermal comfort scale based on the heat balance of the human body. More information about the PMV model can be found in ISO (2005).

However, the ISO standard is valid for specific limits of the environmental and occupational parameters presented by Fanger. As a result, the thermal comfort of an indoor environment can only be assessed according to the ISO standard if measured or estimated values of the six parameters fall within the range of these limits (ISO 2005).

3.4.3 Operative temperature as an indicator

Consequently, applying the full concept of a thermal comfort evaluation might not be possible for indoor environments of which the thermal properties fall far below standardized limits, as described to be the case in rural Nepal (Fuller, Zahnd, and Thakuri 2009). Residents in high altitude regions are further claimed to lack the ability to evaluate comfort as recognized in international standards given the documented wide comfort zones and reports on low neutral temperatures (see section 2.4.4) (Fuller, Zahnd, and Thakuri 2009).

Operative temperature (T_{op}) is a simplified measurement of thermal comfort useful in practice, excluding the complex parameters required for applying the PMV model. Assessing T_{op} is further a required part in full thermal comfort assessments and is defined by ISO (2005) as:

> *"Uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment"*

T_{op} is hence preferred over simply assessing indoor air temperatures in limited comfort assessments since both radiative and convective heat transfer are considered and thus includes the physics of how the thermal climate is perceived (Parsons 2003).

3.5 Hypotheses

Given the background theory and information about the prevalent energy poverty in Nepal, the resulting public health issue of elevated IAP levels in Nepalese kitchens, harsh indoor climates and suggested bioclimatic design for high altitude settlements, the following hypotheses were formulated in the beginning of this study which formed the analytical framework and research methods applied.

Household characteristics influencing IAP levels and thermal comfort

- The majority of the households in Chame is predicted to be reliant on solid biomass to cover daily energy needs, where firewood is expected to be the most commonly used fuel as presented by the Central Bureau of Statistics (2014).
- Open fires or traditional stoves without chimneys are predicted to be the most commonly used cooking and heating devices followed by the ICS, in line with the survey of high altitude regions above 2 000 m.a.s.l. conducted by Nepal Energy Efficiency Programme (NEEP) (2011).

Architectonic features influencing IAP levels and thermal comfort

- Architectonic prerequisites allowing for sufficient natural ventilation in terms of size and prevalence of openings are predicted to be limited due to bioclimatic design features aiming to limit heat losses suggested and confirmed by Bodach, Lang, and Hamhaber (2014) and Toffin (1991).
- Increasing airflow rates through the kitchens by improving the architectonic prerequisites for natural ventilation is expected to reduce IAP levels, as suggested by Still et al. (2011), Singh et al. (2012), Parajuli, H. Lee, and K. Shrestha (2016), and Dhimal et al. (2016). High airflow rates are however expected to have a negative impact on indoor thermal comfort.

Behavioral patterns influencing IAP levels and thermal comfort

- Stove usage and ventilation patterns are predicted to have a significant influence on both IAP levels and indoor thermal comfort in high altitude settlements in Nepal.
- The cooking stoves in Chame are expected to be used for both cooking and heating purposes, as described by Nepal Energy Efficiency Programme (NEEP) (2011) to be common practice in high altitude regions.
- If opening openings at all, taking advantage of natural ventilation is expected to be correlated to stove usage activity in order to avoid smoke accumulation.
- Stove usage patterns are predicted to differ between summer and winter due to an increased demand of heating during colder months of the year, as suggested by Johnson, Edwards, et al. (2014).
- Ventilation patterns are expected to differ between summer and winter both in terms of total opened area and duration of keeping openings opened, being more restricted during colder seasons in order to limit heat losses.

Environmental factors influencing IAP levels and thermal comfort

- Variation in local winds and ambient temperatures in Chame is predicted to influence airflow rates and indoor thermal comfort differently depending on opening configuration (i.e. placement and size of openings). This since natural ventilation is driven by stack and wind effect, both induced by pressure differences determined by local weather conditions as presented in section 3.1.

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4 METHOD OVERVIEW

The aim of this thesis is to assess stove usage and ventilation patterns, resulting indoor air quality and thermal properties of the indoor environment in Nepalese high-altitude kitchens. Alternative passive ventilation strategies are further examined and evaluated with respect to the performance in reducing indoor air pollution levels as well as impact indoor thermal comfort. This chapter outlines the rationale of the research methods applied and provides an overview of the chronology and interdependence of each step in the research process.

4.1 Conceptual framework

In the effort to establish the link between indoor air pollution, passive ventilation and thermal comfort in Nepalese households, interdisciplinary research methods of varying nature were required. As already declared in the Theory chapter, a calculation approach in form of a simplified mathematical model was applied for the IAP assessment. This since field measurements were out of the scope in this study given the limited time and resources, in combination with the aim to simulate and evaluate the efficiency of different passive ventilation solutions. For the same reasons, ventilation associated impacts on indoor thermal comfort were simulated rather than measured in field. Carbon monoxide (CO) was chosen as an indicator for the IAP calculations in line with previous studies aiming to estimate indoor levels of pollutants resulting from indoor burning of solid biomass. The assessment of indoor thermal comfort was conducted with respect to operative temperature only since the indoor thermal environment in Nepal is considered to be below internationally recognized thermal comfort standards where standardized evaluation scales becomes irrelevant (see section 3.3.3 and 3.4.3 for more information). As a result, airflow rates, IAP levels and operative temperatures were all assessed by theoretical calculations and simulations rather than field measurements. Nonetheless, key input parameters for the simulations and calculations were to the largest extent possible based on empirically derived data collected from a specific geographical location of high altitude in Nepal.

4.2 Four-step research process

A four-step research process was conducted within the format of a case study of a high altitude Nepalese village: Chame, Manang (see chapter 2.5 for more information). As suggested in the Theory chapter, both IAP levels and indoor thermal comfort are dependent on the magnitude of airflow rates through the building which in turn is determined by architectonic prerequisites of the kitchen (room volume, prevalence, dimensions and size of openings), household characteristics (stove and fuel type) as well as occupant behavioral patterns (time and duration of stove usage and the practice of opening openings). Site-specific input parameters on physical characteristics of the kitchen environment and behavioral patterns are hence essential when aiming to simulate indoor air quality and indoor thermal comfort representative of the current situation.

As a result, the first step of the research process constitutes of an interview study, providing information required to simulate airflow rates, indoor air pollution levels as well as indoor operative temperatures done in step two, three and four, respectively. In the following section, each step will be presented in chronological order for which an overview of their interdependence is displayed in Figure 6. Detailed information on tools and input parameters of interest for the calculations and simulations will be specified in the following chapter 5: *Method Specification*.

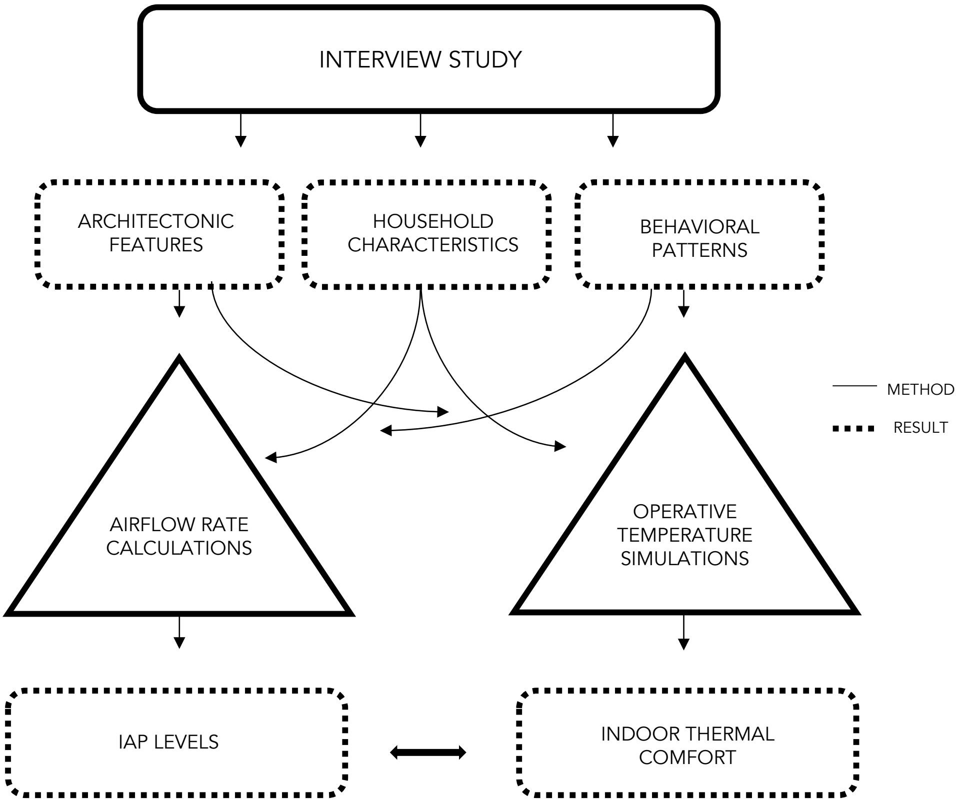

Figure 6: Conceptual chart of the research approach including research methods, partial results and their interdependence.

4.2.1 Step-wise chronology of research process

Step 1: Interview study

An interview study intended to provide essential information on:

- Architectonic features of high altitude kitchens required for the establishment of a base case in form of a physical model from which improved cases with increased ventilation possibilities (different opening configurations) could be developed

- Household characteristics in terms of stove and fuel types used in order to estimate stove related emission factors and generated heat

- Behavioral patterns regarding stove usage and ventilation practices required for the IAP assessment and operative temperature simulations

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Step 2: Airflow rate calculations

Determination of case-specific, weighted average airflow rates based on architectonic features and physical characteristics of the kitchen acquired from Step 1, including local climate data on annual prevalence of ambient temperatures, wind speeds and wind directions.

Step 3: IAP calculations

Assessment of indoor concentrations of CO for each opening configuration case using the airflow rates obtained in Step 2.

Step 4: Operative temperature simulations

Assessment of annual frequencies and diurnal fluctuations of indoor operative temperatures resulting from the different opening configurations, based on stove usage and ventilation patterns obtained from Step 1.

⇒ **Final outcome:** An estimation and evaluation of the current ventilation situation as well as the performance of different opening configurations in reducing indoor air pollution levels and a quantification of the resulting impact of ventilation efficiency on indoor thermal comfort.

4.3 Analytical approach

The empirical data upon which the research questions were to be answered were acquired both by quantitative and qualitative means: Quantitative interviews were performed from which a qualitative selection was extracted and further analyzed. Hence, no statistical probability analysis of the surveyed samples regarding likelihood of exceeding limit values of IAP was performed (see chapter 5.2). An inductive approach was taken on the analysis of the empirical data obtained, since the present research comprise a *theory generating* part in the sense that the correlation between stove usage and the employment of natural ventilation is investigated as well as stove usage and ventilation patterns in Nepalese high altitude settlements are assessed. However, this thesis also includes deductive elements (i.e. *theory testing*), since it aims to answer if the stove is used more in winter than summer for heating purposes, if the practice of opening openings is restricted to limit heat losses due to harsh climate conditions and how different ventilation configurations affect resulting IAP concentrations and indoor operative temperatures.

5 METHOD SPECIFICATION

In the following chapter each step in the research process will be further elaborated. Details regarding calculation approaches, simulation tools and input parameters are provided. Given that early results in the research process serve as a base for the selection of input parameters and methods applied in the following research steps, some results are referred to already in this chapter.

5.1 Step 1: Interview study

5.1.1 Aim

Questionnaires and interviews are acknowledged methods in social research when it comes to gathering necessary data about and from people. The most common types of surveys are *sample* surveys, where a limited number of respondents are to represent a larger group of people (the *population*) (Robson and McCartan 2011). Since the research questions in this thesis are designed to be answered by means of a case study, the establishment of a *base case* representing a typical household for the selected site of study was aimed for. An interview study was therefore conducted, assessing household characteristics in terms of most common type of stove and fuel used as well as behavioral patterns considering time and duration of stove usage and the practice of opening openings (from now on referred to as stove usage and ventilation *patterns*). This in order to provide seasonal and region-specific stove usage and ventilation profiles required for thermal comfort assessments as well as for calculations of stove related IAP.

Along with questionnaire based interviews of which the degree of formality can vary, case studies might also include general observations which together with empirically derived data favourably can be combined with other methods in multi-strategy research approaches (Robson and McCartan 2011). The interview study therefore included an assessment of common architectonic features of the kitchens as well as prevalence, placement and size of different types of openings. This in order to investigate the current physical prerequisites for passive ventilation and the thermal performance of the building envelope, from which improved cases with increased ventilation possibilities could be developed. Sarkar (2013) further confirms that conducting a field survey is the best way to understand the architectural characteristics of a vernacular settlement. To summarize, the main goal with the interview study was to survey:

Architectonic features of kitchen:

- Common kitchen dimensions
- *If* there are any *openable* openings in the kitchen (e.g. windows, doors, hole in wall) and their relative placement

Household characteristics:

- Stove and fuel type
- *If* there are any ventilation systems such as chimneys connected to the stove

Behavioral patterns:

- *If* and *when* the stove is used
- *If*, *when* and *how much* of the present openings that are opened

The complete questionnaire form can be found in Appendix A.1.

5.1.2 Selection of type of interview

There are several types of interview formats which formality and hence suitability depends on the scope and setup of the present study (Robson and McCartan 2011). Structured interviews are used for statistical surveys where the questions are posed and answers registered by an interviewer instead of by the respondents themselves. Within the scope of this study a structured interview was considered suitable due to the rather complex questionnaire setup and the high frequency of illiteracy in rural Nepal. Thus, to reduce the risk of misconceptions and thereby ensure the quality of the data, the structured interview ensures that the questions are well understood, asked in the same manner and in the same order (Robson and McCartan 2011).

5.1.3 Ethical review

The development of an interview study is an extensive task which requires thorough considerations in the formulation of questions when it comes to desirable data and ethical consent. The questionnaire used in this study was revised in line with the criteria presented by the Central Ethical Review Board to eliminate the requirement of official ethical approval (Central Ethical Review Board 2007). In addition, the final version was reviewed by Professor Thorbjörn Laike at the Department of Environmental Psychology at Lund University, Faculty of Engineering.

5.1.4 Sample size and criteria

An accurate sample size is both dependent on statistical delimitations such as level of precision, confidence level and degree of variability as well as demographic data considering the total size of the population in the area of survey (Israel 1992). The sample size can either be calculated according to specific combinations of statistical precision or estimated by tabulated values, of which more information and useful equations can be found in Israel (1992). It should further be noted that sample size formulas represent the number of responses that need to be *obtained*. To compensate for eventual nonresponse, the sampling size is often increased with 10 % − 30 % to cover the total number of surveys desired. Moreover, the analytical method of the empirical data further determines the accuracy of the sampling size and reflects the aim with the study. If the goal is to use the data as *descriptive statistics* i.e. assessing means or frequencies, the accuracy of the data obtained is not dependent on a specific sampling size (Israel 1992).

The interviews in this thesis were performed as a cross-sectional study where the criteria for the households of survey was to be residential. The surveyed subjects were randomly chosen from different clusters of settlements in the geographical spread of the village. Commercial building units such as tea houses and hotels for trekking tourists were avoided in order to only register stove usage and ventilation practices for domestic purposes. Using demographic data for Chame provided by the most recent National Population and Housing Census (NPHC) report published for Manang in 2011 (Central Bureau of Statistics 2014) and standardized tables presented in Israel (1992), an appropriate sampling size could be estimated. With a total number of 262 residential households in Chame, the appropriate sampling size reflecting the obtained responses was suggested to be either 74, 117 or 163 depending on level of precision (± 10 %, ± 7 % and ± 5 % respectively).

5.1.5 Surveyed households and demographic data

Considering the suggested sample size of 74 households for the lowest level of precision including 30 % of nonresponse, the ideal scenario would be to survey around 100 residential households. However, due to the limited time and hardships in finding respondents residing in completely residential houses, a total number of 26 households were surveyed. Yet, due to the fact that the empirical data derived from the interview study was intended to be used for descriptive statistics, the limited number of households surveyed was not considered as a main limitation in the accuracy of the results obtained. Of all households asked, 1 household declined to participate without any specific reason given. Empirical data were hence obtained from a total number of 25 households, forming the statistical basis on which the case study was analyzed.

5.1.6 Analysis of empirical data

In line with the overall aim of the interview study presented above, assessing the current indoor environment in the kitchens of Chame from which improved cases could be developed consisted of three dimensions: determining common architectonic features and opening configurations forming the physical boundaries of a *geometrical* base case, (i.e. a hypothetical kitchen with physical features derived from common observations), common household characteristics in terms of stove and fuel types used as well as to create behavioral profiles based on documented stove usage and ventilation patterns. The methods of which each of these parameters were assessed will be further elaborated in the coming sections.

- **Development of a geometrical base case**

The process of identifying architectonic features representative of kitchens in Chame was performed in two steps. The first step included summarizing the data from all surveyed households on physical characteristics of the kitchen environment where common construction materials and average kitchen dimensions were assessed. Secondly, opening characteristics were analyzed with respect to type, number, orientation, opening situation relative to the stove as well as the possibility to cross ventilate. Opening sizes were based on common dimensions registered for the specific orientation of which openings were found to be most commonly placed, accounting for eventual discrepancies regarding differences in opening area for different orientations due to e.g. common directions of cold winds. As a result, a hypothetical kitchen with geometrical characteristics based on most commonly observed architectonic features was developed.

- **Household characteristics**

The total number of households having *access* to different types of stoves were assessed in order to examine the relative dependence of solid biomass fuels to cover daily energy needs. However, the most commonly *used* stove and fuel combination was further determined for summer and winter since it was found that there was a seasonal difference in stove types used *if* having access to several different stoves. Hence, the surveyed households were divided into different groups depending on stove types used before creating stove usage and ventilation profiles in order to eliminate possible deviations in behavior due to varying smoke levels.

- **Stove usage and ventilation patterns**

Occupant behavior regarding stove usage and the practice of opening openings were recorded by letting the residents specify point in time and duration of each activity for summer as well as winter (see Appendix A.1). Stove usage patterns were assessed as the percentage of households using the stove a certain hour. The ventilation pattern assessment further included a specification of opening type and total opened area per hour. As a result, ventilation patterns were assessed as the average area opened per hour.

- **Stove usage and ventilation correlation**

Stove usage and ventilation practices were compared considering point in time and duration of each activity. This was done by assessing the prevalence of households fulfilling the following criteria:

- Households who use stove but does not open openings
- Households who open openings when not using the stove
- Households who use stove and open openings during stove usage
  - Openings opened before/during/after/when stove is lit?
  - Openings closed before/during/after/when stove is extinguished?

- **Stove usage and ventilation profiles**

Averaged profiles based on the documented behavioral patterns were created as occupant behavior input data in the format required for the airflow rate calculations and operative temperature simulations. In line with the scope of this study, households reliant on solid biomass fuels *only* (i.e. households mainly using biomass-fired cooking stoves to cover their energy needs both summer and winter) served as a base for the stove usage and ventilation profiles employed in further simulations and calculations. Moreover, in order to eliminate eventual disparities regarding the practice of opening openings of certain orientations (e.g. due to local weather conditions as previously mentioned), a specific ventilation profile was created based on the households having the most common orientation of openings reflecting the opening configuration applied in the geometrical base case. For simplicity, the households serving as a base for the stove usage profile employed in the calculations and simulations were selected accordingly. The methods applied to create the behavioral profiles are further described in the following sections.

Stove usage profiles
Time specific "on-off" stove usage profiles aiming to display general practice were developed by first determining the most common duration of stove usage activity throughout the day. Given that peak hours of stove usage were found to be concentrated to some hours in the morning and in late afternoon, this was done by summarizing the total number of hours of having the stove lit during morning (00.00 - 12.00) and afternoon (12.00 - 24.00). The most common point in time of stove usage activity was thereafter determined by integrating over the pillars representing the accumulated percentages of households keeping the stove lit a certain hour, using the time frames assessed in the previous step.

Ventilation profiles
Ventilation profiles were assessed as "meter-square-hours" rather than on an "on-off" basis, illustrating the average opened area each hour. This by summarizing the total area opened throughout the day, averaged over the number of hours representing the most common time of keeping openings opened. Given that a strong correlation between stove usage practice and ventilation habits was found, point in time of taking advantage of natural ventilation was adapted to the stove usage profiles. This in order to ensure that documented interconnections between these activities were reflected in the simulations, enabling the evaluation of possible synergies between stove usage, airflow rates and operative temperatures as requested in the research questions.

5.1.7 Development of different cases

Three different opening configurations were examined with respect to ventilation efficiency, coupled to the performance in reducing IAP levels as well as the resulting impact on indoor operative temperatures. All three opening configurations were based on the original features of the geometrical base case aiming to answer the following questions:

1. **Current situation (Base case): Opened area**

   How much of the available opening area facing outside is actually opened?

   The final opening size applied in the physical model representing the current situation was adjusted according to the findings in the ventilation profile assessment considering the actual *opened* area. The area of each opening type was altered by modifying the width only. This since modifying the height would complicate the analysis of the resulting airflow rates through the building envelope in the simulation tool used. For simplicity, each opening was allocated the same width in the area adjustment, together representing the total area opened. Area adjustment calculations are found in Appendix A.2.2.

2. **Improved case 1: Increase of opened area**

   What is the impact on resulting IAP levels and operative temperature if the opened area is increased?

   The first alternative opening configuration to be examined considers the impact on ventilation efficiency by simply increasing the area of the openings applied in the base case.

3. **Improved case 2: Employment of cross ventilation**

   How does cross ventilation impact IAP levels and operative temperature?

   The second improved case to be investigated considers the impact on ventilation efficiency by adding an opening on the opposite facing wall, given that cross ventilation was not a feature already present in the geometrical base case model.

5.1.8 Limitations

The following *limitations* of the interview study are acknowledged:

- The complexity with being reliant on others conducting the interview study: The risk for subjective formulations when outsourcing the execution of the interview study to *different* Nepali mother tongue speakers is acknowledged considering the language barrier when translating the questionnaire from English to Nepali. Depending on interviewer, multifaceted terms such as the meaning of *ventilation* as the practice of opening openings thus risk to be conveyed differently to the respondents. Furthermore, since I was not able to conduct the interviews myself, I could not ensure that the conversation was held in line with the aim of each question. No nuances of the respondents answers could hence be perceived since I was not a part of the conversation, rather an observant. Thus, supplementary or follow-up questions were hard to pose at the right moment. Additionally, given that there are different Nepali words to express *warm* and *cold* as confirmed by H. Rijal, Yoshida, and Umemiya (2010), important indirect information from discussing the subjective evaluation of the thermal comfort can have been missed to be registered. As a result, I experienced a reduced ability to clarify ambivalent answers from the respondents concerning behavioral practices.

- The fact that the evaluation of what is considered as a warm or cold indoor environment is subjective due to the varying perception of neutral thermal sensation. Stove usage and ventilation practices are subject to the individual habit of adapting to cold conditions thus different stove usage and ventilation practices result from personal preferences of adaptation measures as well as individual physical features.

5.1.9 Delimitations

The following *delimitations* of the analysis of empirical data are acknowledged:

- The size assessment of present openings were based on *openable* areas only. This since one of the main goals with this study was to assess the airflow through the building envelope resulting from different opening configurations. However, it is acknowledged that documenting and including transparent elements in the roof or on exterior walls would have an impact on indoor thermal comfort due to different heat transfer coefficients.

- In the strive to create a base case with general characteristics being somewhat representative for a specific group of households it is vital to acknowledge the complexity of choosing method to determine what is most common versus building the base case on averages. At one point it can be argued how representative average values are considering a diverse survey sample. In this case, both methods were used which surely can be debated as being the optimal and mathematically correct way of ensuring a homogeneous representativeness hence is further acknowledged as a delimitation. Thus, the geometrical base case is to be considered as a hypothetical kitchen of which architectonic features are collected from statistical findings, rather than an actual replica of an existing house in Chame.

- Allocating the same width to each opening in the physical model representing the current scenario is based on the assumption that all openings are opened with the same width. However it is acknowledged that a reduced or increased width of a door would have a larger impact on the airflow rates than a window given the larger height of the door. However, to limit the scope of the study a sensitivity analysis of the impact on resulting airflow rates resulting from opening doors and windows more or less is left for future research.

- It is acknowledged that assessing behavioral patterns for a smaller survey sample is more sensitive for deviating behavior. As a result, investigating general behavioral patterns for all surveyed households or larger categories of groups of households were still considered necessary as a reference to validate the behavior of the rather limited number of households used in the simulations.

- Regarding the creation of stove usage and ventilation profiles, it is well recognized that there might be other more mathematically correct and/or suitable ways of assessing behavioral profiles based on quantitative data:

  - The daily stove usage profile were divided into morning and evening even though there were some households (however a limited number) using their stove during the day as well.

  - Letting the respondents respond in time units of 0.5 hours complicates the creation of ventilation profiles based on averages considering the chosen unit of "meter-square-hours". Having 1 m^2 opened 0.5 hours is not necessarily the same as having 0.5 m^2 opened for 1 hour in terms of resulting airflow rate, hence the round-off rule applied might influence the hourly opened area upon which the profile is based.

- Adapting the area profile to include the hours of stove usage activity by averaging the total area over an extended time period is further recognized as a delimitation regarding mathematical accuracy of translating common observations into statistical determinations. This was however done in order to ensure that statistics of general practice were included in the ventilation profiles rather than basing them solemnly on mathematical rules, risking to exclude vital findings of intertwined activities which have a direct impact on resulting IAP and operative temperature.

- Creating general behavioral profiles are not representative for all households in a surveyed group. The profiles presented rather give an indication on the common practice observed, which however is useful as rough estimations of general user behavior required for simulating operative temperature and indoor air quality resulting from the employment of natural ventilation.

5.2 IAP assessment

General approach

As already introduced in the Theory chapter 3, the IAP assessment was performed by adopting a calculation approach employing a single-zone model dependent on AER and stove related emission factors. This allowed for the investigation of ventilation efficiencies resulting from different opening configuration scenarios while minimizing the need to utilize unjustified assumptions and parameters required in more complex models. Given that the accuracy of single-zone model calculations is determined by the representativeness of the input parameters for the subject of investigation (Johnson, Lam, et al. 2011), site specific data and information from the interview study was used to the largest extent possible.

When it comes to AER, databases providing empirical measurements are limited due to costs and constraints regarding the collection of specific field data, burden for participants as well as access to building restrictions. Moreover, using empirical AER measurements from other buildings come with the uncertainty of airflow rates based on site specific architectonic features and local weather (Breen et al. 2014). As far as the author is concerned, there is no such database for Nepal up to date.

Physical AER models integrated in single-zone pollutant exposure models are further stated as a convenient method of performing epidemiological analyses and risk assessments of indoor air pollution. Surveys of ventilation patterns providing estimations of natural airflows resulting from occupant behavior are allowed to be integrated in physical AER models, enhancing the site specific accuracy of modeled AER (Breen et al. 2014). As a result, a physical model approach was adopted for the AER calculations where airflow rates based on empirically derived data were simulated separately and thereby used in Equation 1.

As the simplified single-zone model applied in this study does not include transient values of AER resulting from diurnal variations in stove usage and ventilation practices, the IAP assessment was performed with respect to the period of active stove usage only. Hence, *static* airflow rates were determined on an hourly basis, taking into consideration the internal heat gain generated by the stove as well as architectonic features such as room volume, infiltration, relative opening placement and opened area. Since naturally induced airflow through a building envelope is dependent on both stack and wind effect resulting from local dynamic weather conditions, airflow rates for each opening configuration case were assessed as weighted averages including the aspect of site specific prevalence of ambient temperatures, wind speed and wind directions.

5.2.1 Step 2: Airflow rate calculations

Aim

The aim with this step was to assess annual weighted averages of airflow rates for each physical model with different opening configurations, taking into consideration annual fluctuations of temperatures, wind speeds and wind directions. This was done by creating:

- Histograms of airflow rates resulting from all opening configuration cases for different temperatures, wind speeds and wind directions, where the ranges were based on annual highs and lows extracted from a local climate file.

- Histograms of annual hourly prevalence of winds speeds for different temperatures and wind directions based on the same site specific climate data.

- Two-dimensional histograms resulting from the product of the two histograms mentioned above, serving as a base for annual weighted averages of airflow rates in l/s.

Simulation tool

Airflow calculations were performed in the energy simulation tool DEROB where airflow rates can be calculated for specific physical models based on local climate files. DEROB considers opening configuration, leakage, temperature differences between inside and outside air (stack effect) as well as wind direction and wind speed (wind effect) when calculating airflow rates induced by natural forces. Thus, both site specific data from the interview study in terms of architectonic features (volume of kitchen, opening configuration, leakage of building envelope), data derived from literature on the amount of stove generated heat as well as information on local weather conditions were required. Climate files were extracted from Meteonorm and used as input data in DEROB.

Physical model specification

All three opening configuration cases presented in section 5.1.7 were built in DEROB for which the naturally induced airflow rates were to be determined. Material selection for the building envelope was based on observations made on the site of study, of which thermal properties were collected from ongoing research on energy efficient building and thermal performance of typical Nepalese construction materials at Kathmandu University. Details regarding the materials employed can be found in Appendix B.1.

Parameter sensitivity

A parameter sensitivity analysis was performed in order to determine influential parameters on simulated airflow rates through the DEROB models. In the following section, a declaration of the most important parameters identified is provided, further specifying the basis on which the assigned values were selected.

Leakage

A database of infiltration rates for different types of Nepalese houses is non-existent. Thus, the leakage parameter used in the simulations was based on unpublished data from field measurements in form of *Blower Door Tests* conducted in the central and southern part of Nepal, in which I personally participated during my time in Nepal. Further information about Blower Door Tests can be found in Breen et al. (2014). An infiltration rate of 10 $l/s/m^2$ at the pressure difference of 50 Pa was thus applied to all opaque elements in the DEROB model, excluding glazed windows. This value is considered to be high, comparing with ASHRAE's suggested default leakage parameter used for residential houses (Sherman 2008). High rates of infiltration are however common in Nepalese houses, as the effective leakage area often can be observed as clear gaps between walls and roof as well as between openings and walls as shown in Figure 7. High infiltration rates for Nepalese houses have further been used by Manandhar and Yoon (2015) and Fuller, Zahnd, and Thakuri (2009) who similarly aimed to simulate the indoor environment in an energy simulation tool.

(a) Gaps around a door. (b) Gaps in the ceiling.

Figure 7: Visual sources of leakage in building envelopes in Chame.

Limitations

- Blower Door Tests were not conducted in high altitude regions of Nepal. This is recognized as a limitation in the validity of leakage input parameter used for simulating airflow rates representing high altitude settlements of Chame. However, due to the fact that this is up to date the first attempt to assess infiltration rates in Nepalese houses, it was considered more legitimized to use empirical measurements on leakage rather than to make crude estimations on observations made in Chame. Thus, the leakage parameter of 10 $l/s/m^2$ at the pressure difference of 50 Pa reflects an average of leakage parameters obtained for buildings with similar architectonic features in terms of type of construction and effective leakage area in the lack of site specific data.

Internal source of heat

Internal heat gains were attributed to the heat generated by the biomass fired cooking stove only, here referred to as *stove size* assessed in Watts (W or J/s). The stove size was calculated based on data derived from literature on *lower heating value* (LHV) of the fuel in MJ/kg and *fuel burning rate* in kg/h for stove types and fuels similar to what was observed in Chame. Laboratory tests have been performed for metallic stoves with chimneys distributed in the village of Jumla, situated in a similar geographic region and altitude as Chame (2 500 m.a.s.l). Considering an energy input of 100 %, 40 % is claimed to be available for cooking or heating purposes since roughly 60 % of the energy was found to escape through the chimney (Thakuri S. 2006). After consulting the author Dr. Alex Zahnd, the stove size entered in DEROB was based on these findings and hence calculated by Equation 5:

$$W_{stove} = 0.4 \cdot \frac{LHV_{fuel} \cdot F_{rate}}{3\ 600} \tag{5}$$

where W_{stove} represents the internal heat gain generated from the stove in W, 0.4 the percentage of energy content in the fuel reaching the indoor environment in case of a chimney, LHV_{fuel} the energy content in the fuel in MJ/kg, F_{rate} the fuel burning rate in kg/h and 3 600 the number of seconds per hour. Input parameters valid for firewood was used in the calculations, being the most common type of solid biomass fuel used in Chame. With a LHV_{fuel} of 17 MJ/kg and an average F_{rate} of 2 kg/h derived from average values found in literature, a stove size approximated to 4 000 W was used in the DEROB model, falling within the same range as the stove power of 4 900 W found for a traditional *Chula* stove in Johnson, Lam, et al. (2011)'s assessment of IAP from different stove types. A specification of the selected input parameters is found in Appendix C.1.

Limitations

- The contribution of heat from the stove to the indoor environment is dependent on the overall thermal efficiency (OTE) of the stove, which varies widely among improved cooking stove designs due to the lack of a consistent definition of an ICS. This was further highlighted by Dr. Zahnd who confirmed that the term *stove efficiency* is ambiguous and used differently among researchers. In combination with that the calorific value of firewood varies with geographic location and moisture content (Jetter et al. 2012), Dr. Zahnd acknowledge the difficulty with comparing different researchers' results. Nonetheless, the numbers provided in Thakuri S. (2006) on internal heat gains resulting from chimney stoves were still declared as reasonable within the rather large accuracy possible of a combustion process, which in turn was claimed to be inherently difficult to measure. Furthermore, the performance of stoves in laboratory settings is stated to deviate from the performance in field (Edwards et al. 2014). Thus, it is important to note that the stove size obtained from the calculation in Equation 5 only is a rough estimation aiming to represent the internal heat gain generated by the stove types observed in Chame.

- Since the fuel burning rate (F_{rate}) also is stove type dependent, data on F_{rate} for similar stoves as observed in Chame was aimed for. Fuel consumption reported from field studies based on systematic weighing of fuel however differs from laboratory tests (Smith et al. 2007). Moreover, the improved cooking stoves observed in Chame were not properly used, risking to further deviate from fuel consumption rates assessed in laboratory conditions. This is hence acknowledged as a limitation in the aim to simulate a scenario representative of field observations made in Chame.

DEROB simulation procedure

Simulations were run with constantly opened openings and a constant internal heat source since static airflow rates for the duration of cooking only were to be determined for different combinations of temperatures, wind speeds and wind directions for each opening configuration. A modification of the original climate file was hence necessary. Hourly variations of weather parameters were substituted by matrixes of set ranges of temperatures, wind speeds and wind directions, based on annual highs and lows extracted from the original climate file. Incoming solar radiation was further deactivated. An extract from the modified climate file used to simulate airflow rates in the kitchens with single sided ventilation is presented in Figure 8.

Histograms: Partial results

Airflow rates

Histograms were created in Excel displaying the magnitude of airflow rates for each opening configuration resulting from the different combinations of weather parameters. In case of single sided ventilation, variation in temperature and wind speed served as a base for the histogram calculation due to the marginal influence by wind direction found in a sensitivity analysis performed in DEROB. The histogram matrix was hence based on one set wind direction of 45^o, which together with 135^o were shown to have the largest impact on the resulting airflow rates (however insignificant compared to the influence of temperature).

The improved case with cross ventilation was however based on variations in wind speed and wind direction since both these aspects of the wind effect was proven to override the stack effect driven by indoor and outdoor temperature differences. Hence, a set temperature of 5 ^{o}C was selected to serve as a base for the histogram matrix among the temperatures simulated, being closest to the annual average temperature found to be around 6 ^{o}C. The relationship between ventilation rate and wind direction is however non-linear around the unity circle (0^o – 360^o). Airflow rates resulting from wind directions of 0^o – 90^o and 90^o – 180^o rather follow the pattern of a sinus curve. To account for this sensitivity, airflow rates were assessed for wind directions of each 30^o instead of each 90^o as done for the case of single sided ventilation.

```
C Site name: Chame
C 1:st Day: 2005.01.01
C Last Day: 2005.12.31
C
C Latitude:        28.52 (Pos. to North)
C Longitude:       84.24 (Pos. to East)
C Time Meridian:   87.50 (Pos. to East)
C
C records: Year, Month, Day, Hour, Tout, Xout, IdH, IN, Tsky, Winddir, Windspeed
C Format:  (i4,3i3,1x,f7.1,f8.4,5(1x,f7.1))
C
2005  1  1  1   -15  39  0  0  -29.4  45   1
2005  1  1  2   -15  39  0  0  -29.4  45   1
2005  1  1  3   -15  39  0  0  -29.4  45   1
2005  1  1  4   -15  39  0  0  -29.4  45   1
2005  1  1  5   -15  39  0  0  -29.4  45   3
2005  1  1  6   -15  39  0  0  -29.4  45   3
2005  1  1  7   -15  39  0  0  -29.4  45   3
2005  1  1  8   -15  39  0  0  -29.4  45   3
2005  1  1  9   -15  39  0  0  -29.4  45   5
2005  1  1  10  -15  39  0  0  -29.4  45   5
2005  1  1  11  -15  39  0  0  -29.4  45   5
2005  1  1  12  -15  39  0  0  -29.4  45   5
2005  1  1  13  -15  39  0  0  -29.4  45   7
2005  1  1  14  -15  39  0  0  -29.4  45   7
2005  1  1  15  -15  39  0  0  -29.4  45   7
2005  1  1  16  -15  39  0  0  -29.4  45   7
2005  1  1  17  -15  39  0  0  -29.4  45   9
2005  1  1  18  -15  39  0  0  -29.4  45   9
2005  1  1  19  -15  39  0  0  -29.4  45   9
2005  1  1  20  -15  39  0  0  -29.4  45   9
2005  1  1  21  -15  39  0  0  -29.4  135  1
2005  1  1  22  -15  39  0  0  -29.4  135  1
2005  1  1  23  -15  39  0  0  -29.4  135  1
2005  1  1  24  -15  39  0  0  -29.4  135  1
2005  1  2  1   -15  39  0  0  -29.4  135  3
2005  1  2  2   -15  39  0  0  -29.4  135  3
```

Figure 8: Extract from the modified climate file employed in the simulations of static airflow rates at different combinations of temperatures, wind directions and wind speeds for the kitchens with single sided ventilation. This extract illustrates input data for the temperature of -15 ^{o}C, wind directions of 45^{o} and 135^{o} and wind speeds ranging from 1 m/s to 9 m/s.

Site specific prevalence of temperature, wind speed and wind direction

Histograms of the annual prevalence of wind speeds were created on an hourly basis based on the original climate file. Annual rather than seasonal prevalence was assessed under the pretext that there was no significant difference in area opened between the summer and winter profiles hence that the same physical model could be used for yearly simulations in DEROB. In case of single sided ventilation, prevalence of wind speeds within specific ranges of temperature was assessed as displayed in Table 8. In case of cross ventilation, prevalence of wind speeds within specific ranges of wind directions was assessed instead as displayed in Table 9.

Table 8: Annual prevalence of hours with certain wind speeds in Chame for specific ranges of temperatures, serving as a base for weighted average calculations for the cases with single sided ventilation.

Annual prevalence / hours					
Temperature / °C	[-20; -10 [	[-10; 0 [	[0; 10 [	[10; 20 [	[20; 30 [
Wind speed / (m/s)					
2	145	1389	1788	1980	80
4	44	532	976	914	73
6	8	114	292	258	18
8	4	13	56	51	3
10	0	3	15	4	0

Table 9: Annual prevalence of hours with certain wind speeds in Chame for specific ranges of wind directions, serving as a base for weighted average calculations for the case with cross ventilation.

Annual prevalence / hours												
Wind direction / °	[0 ; 30 [	[30 ; 60 [	[60; 90 [	[90 ; 120 [	[120 ; 150 [	[150 ; 180 [	[180 ; 210 [	[210 ; 240 [	[240 ; 270 [	[270 ; 300 [	[300; 330 [	[330; 360 [
Wind speed / (m/s)												
2	329	458	635	710	759	287	181	177	237	560	671	378
4	174	196	263	350	316	113	100	72	136	295	295	229
6	63	69	67	79	88	24	17	33	26	72	75	77
8	12	3	4	17	14	3	5	5	4	16	24	20
10	2	1	1	3	4	1	2	1	1	2	3	1

Airflow rates resulting from different opening configurations

Airflow rates for the opening configuration cases of investigation (current situation, increase of opened area and cross ventilation) resulting from the different wind speeds, temperatures and wind directions are presented in Table 10, 11 and 12.

Table 10: Airflow rates through the kitchen volume with the single sided opening configuration representing the current ventilation situation, resulting from different wind speeds and temperatures for a set wind direction of 45^o.

BASE CASE	Airflow rates / (l/s)				
Temperature / °C	-15	-5	5	15	25
Wind speed / (m/s)					
1	230,7	207,8	202,3	197,5	191,0
3	247,3	241,1	235,3	229,9	224,1
5	270,6	264,0	258,0	251,9	245,4
7	299,1	291,8	285,2	278,3	271,5
9	333,5	325,6	318,0	310,7	303,2

Table 11: Airflow rates through the kitchen volume with increased opened area of single sided ventilation, resulting from different wind speeds and temperatures for a set wind direction of 45^o.

INCREASED OPENED AREA	Airflow rates / (l/s)				
Temperature / °C	-15	-5	5	15	25
Wind speed / (m/s)					
1	374,5	351,0	342,1	334,8	326,6
3	392,9	383,4	373,9	365,6	355,9
5	413,5	403,7	395,0	385,0	374,9
7	439,2	428,7	419,1	409,0	398,4
9	468,9	458,0	447,4	436,7	425,9

Table 12: Airflow rates through the kitchen volume with cross ventilation, resulting from different wind speeds and wind directions for a set temperature of 5 ^{o}C.

CROSS VENTILATION	Airflow rates / (l/s)											
Wind direction / °	15	45	75	105	135	165	195	225	255	285	315	345
Wind speed / (m/s)												
1	244,5	282,1	314,9	314,8	274,0	236,6	238,0	272,6	308,1	308,2	267,0	233,8
3	311,9	592,8	816,9	816,9	592,7	311,5	303,8	590,0	814,9	814,9	590,0	304,7
5	402,5	997,8	1378,3	1378,3	997,8	401,6	395,1	996,3	1377,0	1377,0	996,4	396,7
7	533,7	1409,1	1949,0	1949,0	1409,0	533,7	530,6	1407,8	1947,7	1947,7	1407,8	530,7
9	691,6	1825,0	2526,7	2526,7	1825,0	691,6	689,5	1823,7	2525,3	2525,3	1823,8	689,7

Two dimensional histograms as a mean to calculate weighted averages

Two dimensional histograms were created by multiplying the histogram matrix representing annual prevalence of wind speed ranges (see Table 8 and 9) with the airflows resulting from the specific wind speeds obtained from the DEROB simulations (see Table 10, 11 and 12). From this matrix, the annual weighted average of resulting airflow rates could be determined on an hourly basis by dividing the sum of all products with the total number of hours in a year. Two dimensional histograms for each opening configuration are presented in Figures 9, 10 and 11.

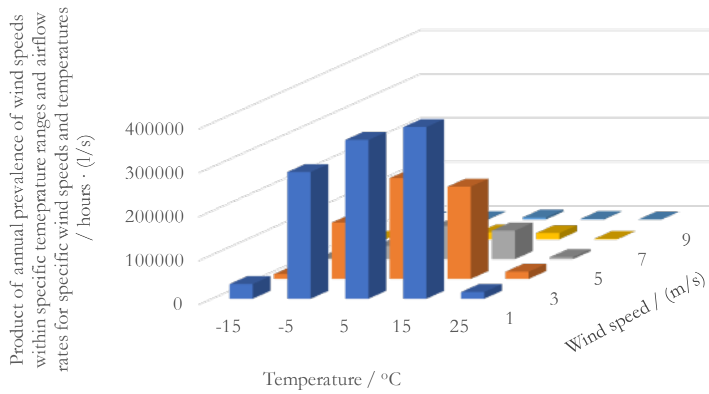

Figure 9: Two dimensional histogram displaying the product of 1. Annual hourly prevalence of wind speeds in Chame within specific temperature ranges, and 2. Airflow rates that different wind speeds generate through the kitchen volume representing the current situation.

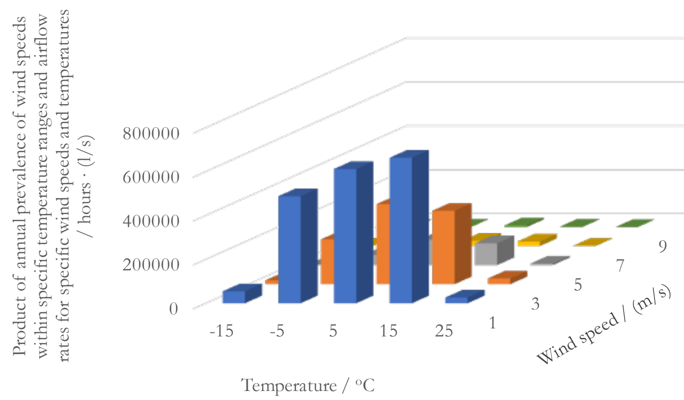

Figure 10: Two dimensional histogram displaying the product of 1. Annual hourly prevalence of wind speeds in Chame within specific temperature ranges, and 2. Airflow rates that different wind speeds generate through the kitchen volume with increased area of single sided ventilation.

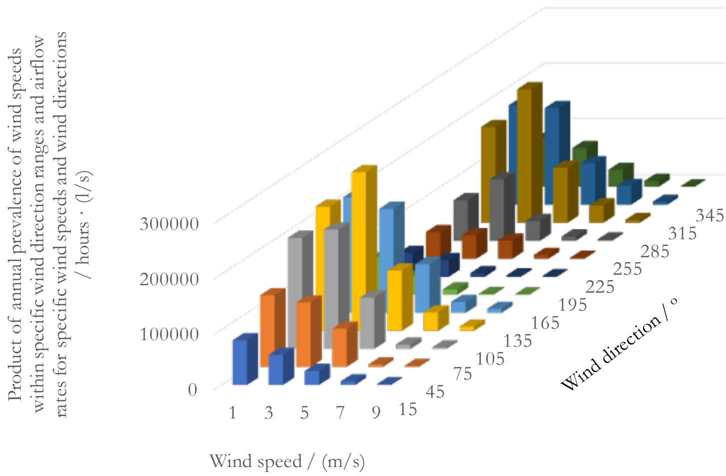

Figure 11: Two dimensional histogram displaying the product of 1.Annual hourly prevalence of wind speeds in Chame within specific ranges of wind directions, and 2. The resulting airflow rates that different wind speeds generate through the kitchen volume with cross ventilation.

Limitations

- The basis upon which the weighted average airflow rates are calculated combine the annual prevalence of certain weather parameters and resulting airflow rates as a mean to include the frequency and magnitude of "*inconvenience*" occurring from different wind speeds. It is however acknowledged that there might be other ways of determining weighted averages based on site specific climatic conditions.

- The airflow rates presented are not to be considered as annual averages of airflow rates flowing through the building models. This since airflows are assessed for the period of cooking time only, excluding diurnal changes in stove usage and ventilation patterns throughout the year since this would include hours when the stove is not used and openings are kept close.

- DEROB has not previously been employed for static airflow rate calculations. It is thereby acknowledged that a comprehensive parameter sensitivity analysis have the potential to optimize the selection of constant values in the modified climate file, improving the accuracy of obtained airflow rates.

5.2.2 Step 3: IAP calculations

Aim

The aim with this step was to assess indoor concentrations of CO resulting from different opening configurations of hypothetical kitchens, based on stove specific emission factors, emission rates, fractions of fugitive emissions as well as AER calculated from airflow rates derived from Step 2. This in order to correlate ventilation efficiency to indoor air quality, in line with the research objectives of:

- Assessing the ventilation efficiency of the current ventilation situation considering the accumulation of IAP generated by indoor burning of solid biomass fuels, put in relation to WHO and Nepalese IAQ guideline values.
- Examine the ventilation efficiency provided by alternative opening configurations considering the ability to reduce the accumulation of IAP to not exceed WHO or Nepalese IAQ guideline values.

Calculation approach

IAP calculations were performed in Excel where a simplified single-zone model was created. The Excel model considers a control volume assuming perfect mixing where pollutant emissions are modeled as a point source with constant emission rate E_r. Potential contributions from outdoor air or backflow from chimneys were excluded. No other means of pollutant reduction than natural ventilation was considered since the relative reduction from different opening configurations were to be evaluated. Incoming and outflowing airflow rates were presumed to be equivalent. Pollutants were assumed to enter the kitchen and instantaneously mix to homogeneity before a fraction of the polluted air was exchanged with fresh air. The resulting concentration CO at the time t (C_{t+1}) was thereby be calculated as:

$$C_{t+1} = (C_t + \frac{FE_f t}{V})(1 - AER) \tag{6}$$

where C_t is the concentration CO in g/m^3 accumulated from previous time steps, F the fuel burning rate in kg/s, E_f the pollutant emission factor in g/kg resulting from the stove and fuel combination, t the time in seconds, V the volume of kitchen in m^3 and AER the air exchange rate per second (s^{-1}). A fine time step scale of seconds was required in order to ensure that CO concentrations would not turn negative for high AER. Equation 6 was validated by employing the same emission factors, volume and AER as was used by Zhang et al. (1999a) in a similar IAP assessment, comparing the resulting concentrations of CO.

Input parameters

AER

As previously mentioned, the accuracy of pollutant concentration estimations derived from single-zone models depends on the reliability of input parameters including integration of local data (Ruiz and Masera 2018). The AER for each opening configuration was hence calculated according to Equation 1, based on the airflow rates derived from Step 2 including site specific architectonic features and local climate files.

E_f

In the absence of field measurements on pollutant emission rates, stove related emission parameters were extracted from an extensive literature review. Since the emission factor E_f depends on stove and fuel combination, values for stoves best representing the stove and fuel types used in Chame was aimed for. The stoves observed in field did however not represent a clear cut case even if the majority of the households were found to use wood-fired ICS fitted with chimneys. All stoves documented as an ICS were however of rectangular shape, made of metal and had a chimney. Nonetheless, the improved features as well as the general appearance varied due to different manufacture origins. Some were subsidized and distributed by AEPC through the governmental action plan of *Clean Cooking Solutions for All 2022*, and some were locally customized or even self made. The subsidized stoves had chimneys as well as features improving combustion efficiency (e.g. leveled combustion chamber and/or a chimney baffle), whereas the locally customized and self made stoves were only fitted with a chimney and often lacked a fire gate (i.e. a gate allowing to enclose the combustion chamber after fueling) as shown in Figure 12. The majority of the metal stoves were hence tended as traditional stoves or open fires resulting in that a substantial part of the fire was taking place outside of the combustion chamber. Additionally, the quality of the chimneys was differing between the stoves, where weaknesses in overlapping metal sheets around the joints were noted. In combination with the inconsistency in ICS emission reduction performance presented in section 3.2.5 in the Theory chapter, a mean of E_f for both metallic and traditional stove types presented in Table 13 was used in the calculations, resulting in 85.9 g CO/kg wood.

(a) Locally manufactured metal stove.

(b) Subsidized metal stove with fire gate.

Figure 12: Metal stoves fitted with chimneys observed during the interview study.

Table 13: Emission factors E_f of CO in g/kg fuel for different wood-fired stove types documented from field measurements as well as in laboratory conditions.

Source	Country	Field vs. Lab	Stove type	E_f / (g/kg)
Davidson et al. (1986)	Nepal	Field	Traditional mud	70
Edwards (2015)	Nepal	Field	Traditional Clay	107
Zhang et al. (1999a)	India	Field WBT	Metallic	74
Bhattacharya, Albina, and Salam (2002)	Nepal	Lab WBT	Ceramic/metallic one pot	136
Bhattacharya, Albina, and Salam (2002)	Nepal	Lab WBT	Ceramic two pot	113
Jetter et al. (2012)	USA	Lab WBT	Open fire (average)	48.5
Edwards et al. (2014)	World averages	Lab WBT	Traditional (unvented)	52.8

E_r

E_f and F in Equation 6 was substituted by the emission rate E_r as displayed in Equation 4 in section 3.2.4. The same fuel consumption rate for firewood of 2 kg/h as used in the airflow rate simulations was applied. Ideally, a stove fitted with chimney would vent out all pollutants generated in the combustion chamber. However, a substantial smoke accumulation was observed in field hence fugitive emissions were accounted for by multiplying E_r with a *chimney capture efficiency* or *chimney reduction potential* (σ) as suggested by Johnson, Edwards, et al. (2014). E_r was hence redefined as:

$$FE_f = \sigma E_r \tag{7}$$

Due to the complexity of visually determining the fraction of smoke entering the kitchen, in combination with the lack of documentation and inconsistent reporting on chimney performance in field as presented in Table 5 in section 3.2.5, indoor concentrations of CO for a range of chimney capture efficiencies were assessed: 30 %, 69 % and 90 %. The span of the range was defined in line with AEPC's declaration of overall ICS reduction potentials of 30 % to 90 % less pollutants reaching the indoor environment (M. Thapa and Subba 2015). The chimney capture efficiency of 69 % represents an average between the two reduction potentials presented in Table 5 based on hourly assessments of IAP levels, thus most applicable to the calculations performed in this study. Fugitive emissions for chimney stoves with chimney capture efficiencies of 30 %, 69 % and 90 % were hence accounted for by multiplying E_r with 0.7, 0.31 and 0.1 respectively.

Format of results

Graphs displaying transient concentrations of CO for up to one hour of stove usage activity and CO decay rates when the stove is extinguished and openings kept opened. Indoor concentrations of CO resulting from different levels of fugitive emissions are presented for all opening configuration cases and put in relation to IAQ guidelines.

Limitations

- The single-zone model is based on the assumption of perfect mixing. However, the distribution of IAP resulting from a hot point source such as a biomass-fired cooking stove is claimed to be vertically stratified in reality (Johnson, Edwards, et al. 2014; Still et al. 2011). CO concentrations in particular have been presented to vary in both time and space (Smith 2014; Balakrishnan, Mehta, et al. 2014). Estimating indoor concentrations of CO with a single-zone model approach is hence acknowledged to deviate from empirically measured concentrations in different parts of the kitchen (Johnson, Lam, et al. 2011). The assumption of perfect mixing is however a prerequisite for simplified IAP calculation approaches in order to go about empirical measurements.

- Given that the accuracy of the single-zone model is determined by the representativeness of the input parameters, using mean values of emission factors and fuel consumption rates derived from literature is acknowledged to compromise the validity of the calculations and resulting IAP concentrations. Nonetheless, the variation in quality of the stove types observed in Chame combined with inconsistent reports on ICS performance obstruct the determination of the most representative stove related input parameters. Moreover, no consideration to altitude associated pressure differences was included in the concentration calculations.

- The calculation approach applied includes a single pollution source with constant emission rate. Yet, in reality emissions rates fluctuate during the combustion process due to variations in firepower in turn being dependent on cooking or heating need, of which more information can be found in Kshirsagar and Kalamkar (2014).

- The magnitude of fugitive emissions reaching the indoor environment from a chimney stove is the sum of leakage from flue joints, badly fitting pots and operational behavior etc (Reid, Smith, and Sherchand 1986). It is however complex to distinguish the relative contribution from different sources to the overall fugitive emissions. As a result, fugitive emissions were accounted for by only including a general *chimney* capture efficiency in the estimation of E_r. However, performing calculations for a range of capture efficiencies serves as a sensitivity analysis and a mean to account for varying levels of fugitive emissions regardless origin. Thus, it is important to acknowledge that the calculated levels of CO is an approximation of the *total* percentage of smoke generated in the stove combustion chamber reaching the indoor environment.

- The scope of this study only covers CO levels generated by fugitive emissions originating from the stove and chimney, excluding potential contributions from the surrounding environment such as pollutants from nearby homes or re-infiltration through openings due to inappropriately placed chimneys. This further stresses the importance of considering the estimated levels of CO as relative rather than absolute.

- The same airflow rates used to calculate indoor concentrations of CO during stove usage are applied to investigate the CO *decay rate* i.e. the time required to keep openings opened after the stove is extinguished in order for CO levels to reach safe limits. Hence, the airflow rates basing the CO decay rates do not consider the potential stack effect difference for when the stove is extinguished but still serves as a source of radiant heat. More specifically, the corresponding reduction in stove power within the first minutes after stove usage is not accounted for. As a result, CO decay rates are to be viewed as an effort to estimate approximate time frames to reach safe levels of CO rather than exact number of minutes required.

5.3 Step 4: Operative temperature assessment

5.3.1 Aim

The final part of this thesis comprise the investigation on how indoor thermal comfort is affected by the natural ventilation rates resulting from different opening configurations. Hence, the aim with this step is to present seasonal distributions, quantify the annual prevalence and display diurnal fluctuations of indoor operative temperatures for all opening configuration cases examined, in line with the research objectives of:

- Evaluate the current ventilation situation as well as alternative passive ventilation strategies considering the resulting impact of ventilation efficiency on indoor thermal comfort.

5.3.2 Simulation tool

As for the airflow rate calculations, the assessment of indoor operative temperatures was conducted in the energy simulation tool DEROB. DEROB is usually employed for thermal comfort assessments providing information of PMV and PPD in line with the ISO standard as presented in section 3.4.2. However, explicit information on hourly fluctuations of operative temperature is also provided, taking into consideration internal heat gains, local climate, air exchange rates resulting from physical features of the model (construction materials as well as prevalence, orientation and size of openings) and behavioral patterns (frequency and duration of opened openings and internal heat gains from the stove). DEROB calculates operative temperature according to the following equation:

$$T_{op} = \frac{T_v + (\sum T_i \cdot A_i)/\sum A_i}{2} \tag{8}$$

where T_{op} is the indoor operative temperature, T_v the indoor temperature for the volume and T_i the temperature of the enclosing surfaces. All temperatures are assessed in degrees Celsius (^{o}C). A_i represent the total surface area of the enclosed volume in m^2. Since the scope of this study includes the aim to investigate the influence of a varying degree of naturally induced airflow on indoor thermal comfort, DEROB's quality of including local climatic conditions (indoor-outdoor temperature differences, solar gains, wind directions and wind speeds) was considered vital since airflow rates through a building envelope is driven by both stack and wind effect (see section 3.1). Climate data was extracted from Meteonorm as done for the airflow calculations. In addition, using the same simulation tool for both airflow rate calculations and operative temperature simulations where the same physical models can be used, facilitates comparisons and evaluations between indoor air quality resulting from different opening configurations and the respective influence on thermal comfort.

5.3.3 Simulation procedure and input parameters

Simulations of annual indoor operative temperatures were run in DEROB for all three opening configuration cases under investigation: current situation (base case), increase of opened area as well as cross ventilation. Input parameters of interest are specified below.

Physical model specification

The same physical models used for the airflow rate calculations were employed in the operative temperature simulations. A graphical display of the models are presented in Figure 24 in chapter 6: *Results*.

Behavioral patterns

Stove usage and ventilation profiles derived from the interview study in Step 1 were entered in DEROB, specifying frequency and duration of having the stove lit as well keeping openings opened throughout the year. Stove usage profiles were entered as an internal heat gain. Ventilation profiles providing information on averaged opened area over time were entered accordingly.

Seasonal differences

As it was found that behavioral patterns differed between summer and winter, seasonal schedules on stove usage and ventilation practices were entered in DEROB. An analysis of the local climate file was conducted in order to compare site specific data of ambient temperatures with the defined seasons presented by Bodach, Lang, and Hamhaber (2014), where winter is considered as October to March and summer from April to September. The approach of the analysis comprised a seasonal division where the following two frames of reference were applied: assessing months with minimum ambient temperatures of below 0 ^{o}C to represent winter, and months with maximum temperatures above 20 ^{o}C to represent summer. As shown in Figure 13, the maximum temperature in April does not reach 20 ^{o}C and the minimum temperature drops well below zero. Even minimum temperatures in May were found to be slightly below zero, however, when scrutinizing the relative distribution of total number of hours below freezing, April was shown to have 134 hours with temperatures between -6 ^oC to 0 ^oC, whereas only 17 hours in May fall in the range of -2 ^oC to 0 ^oC. Summer profiles in DEROB were hence entered from May through September, and winter profiles from October to April, reflecting a compromise between local climate data and the more general division of seasons in Nepal. A monthly overview of the relative prevalence of ambient temperatures in Chame is displayed in Figure 14. Seasonal stove usage and ventilation profiles are presented in Figure 21 and 23 in chapter 6: *Results*.

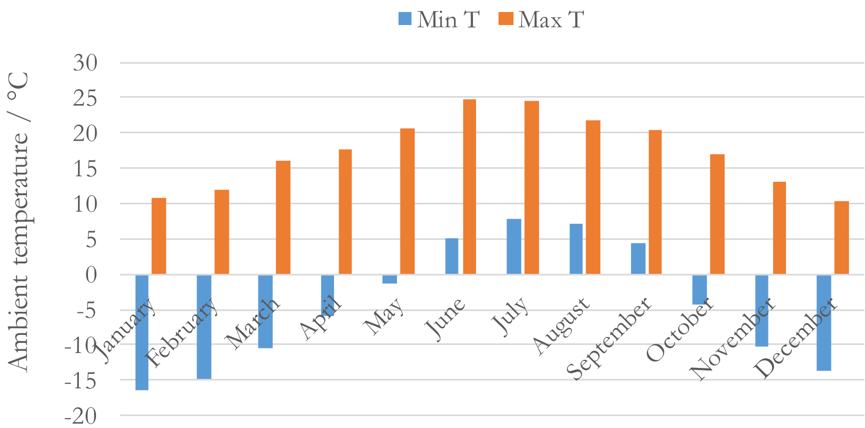

Figure 13: Monthly minimum and maximum temperatures in Chame.

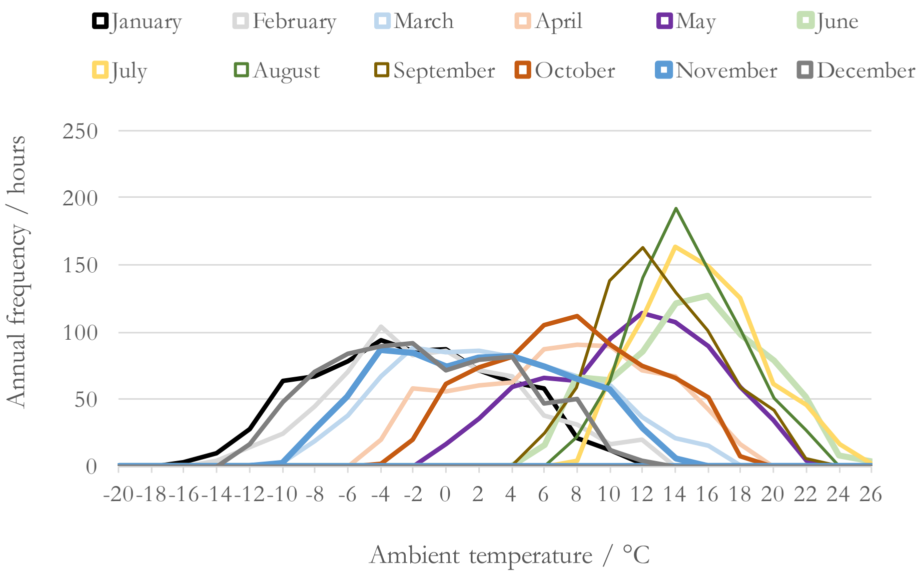

Figure 14: Prevalence and distribution of monthly ambient temperatures in Chame.

Leakage and stove size

The leakage parameter and stove size were attributed the same values as in the airflow rate calculations. Detailed information on these parameters is presented in section 5.2.1 of Step 2: *Airflow rate calculations.*

5.3.4 Format of results

Graphs and histograms displaying the seasonal distribution and annual prevalence of indoor operative temperatures in kitchens with different air exchange rates resulting from different opening configurations. Annual frequencies of indoor operative temperatures below 10 ^{o}C and 0 ^{o}C are highlighted as a measure on thermal discomfort. Graphs comparing the different cases for a specific day in summer and winter are further provided in order to display the diurnal dynamics of indoor operative temperatures resulting from seasonal differences in stove usage, ventilation practices and climatic conditions.

Limitations

- The scope of this study covers the evaluation of indoor operative temperatures resulting from varying airflow rates generated by different opening configurations only. A change in behavioral practice is hence not included in the alternative ventilation strategies investigated.

- Stove usage and ventilation profiles applied in DEROB are generalized patterns. Consequently, the results obtained do not display absolute temperatures for specific households in Chame. Rather, the operative temperatures presented are to be viewed as thermal conditions given certain prerequisites where the aim is to evaluate the relative influence of different opening configurations.

- In DEROB the placement of openings on the same wall for a specific control volume does not matter. Thus, DEROB does not allow for testing different placements of windows on the same wall to find an "optimal" ventilation situation considering resulting air exchange rates and indoor operative temperatures.

6 RESULTS

In the coming sections, the results of this study will be presented in the chronological order of the four-step research process as described in chapter 4 and 5: Method overview and Method specification.

6.1 Interview study

In line with the chronology of the analysis of the empirical data, the results from the interview study will be presented in the following order:

1. Architectonic features
2. Specification of geometrical base case
3. Household characteristics
4. Behavioral patterns
    - Stove usage and ventilation correlations
    - Stove usage and ventilation profiles
5. Presentation of the three different opening configuration cases
6. General observations

Given that early results from the interview study provide input parameters required for the consecutive research steps, some of the formulations in the coming sections are acknowledged to be of a descriptive and justifying nature, originally more associated with contents presented in method chapters.

6.1.1 Architectonic features

Empirical data on architectonic features of kitchens acquired from all 25 surveyed households serving as a base for the formulation of the geometrical base case is provided in the following sections.

Kitchen layout

As presented in Table 14, the majority of the surveyed households have only one floor in the house suggesting that the most common placement of the kitchen is on the ground floor. Table 14 further presents that 76 % of the households have separate kitchens, meaning that the kitchen environment is enclosed from other rooms which in turn indicate that the dwelling unit most commonly consist of more than one multi-purpose room in which the stove is situated. However the remaining 24 % of the kitchens are hence used for other purposes except from cooking and eating. Half of these households (12 %) were documented to only have one room in the house indicating that these residents sleep in the same room as the stove is placed.

Table 14: Specification of most common placement of the kitchen in residential houses in Chame.

Architectonic features of the residential unit and kitchen		
Number of floors	Number of households	Percentage of households
1	**19**	**76 %**
2	5	20 %
3	1	4 %
Separate kitchen		
Yes	**19**	**76 %**
No	6	24 %
Only one room in house	3	12 %

Observational facts

Some of the separate kitchens were not only enclosed from other rooms by opaque walls. Several kitchens were observed to be situated in a separate part of the building or as a separate building adjacent to the residential unit in the courtyard. Often this was the case for large two-floor, multifamily, mud and brick bonded houses with wooden balconies, further noted as typical architectonic features of residential houses in Chame as displayed in Figure 15.

Figure 15: Example of a separate kitchen built in wood adjacent to the residential unit.

Kitchen volume

Table 15 displays the average kitchen volume based on mean values of documented kitchen dimensions of length, width and height of all surveyed households.

Table 15: Specification of average kitchen dimensions of all 25 surveyed households and the resulting volume.

Average kitchen dimensions	
Average length / m	4
Average width / m	3,2
Average height / m	2,2
Average volume / m^3	**28,16**

Opening specification

Opening types facing outdoor environment

Table 16 presents the prevalence of all surveyed kitchens having specific opening types. Here it can be seen that 96 % have an outer door to enter the kitchen. Roughly 50 % of the surveyed households have at least one window. However, all kitchens with windows have at least one outer door as well. One household (4 %) was found to have a hole in the roof providing constant ventilation.

Table 16: Prevalence of households having specific types of openings facing outside.

Opening specification		
Type of opening	**Number of households**	**Percentage of households**
Window	13	**52 %**
Door	24	**96 %**
Both window and door	13	**52 %**
Hole in wall	0	0 %
Hole in roof	1	4 %

Number of openings

Table 17 suggests that the majority of the surveyed kitchens with openings facing outside have only one of each opening type considering windows and doors. This was further confirmed by investigating the most common ranges of number of openings observed (see Appendix A.2.1). The range of a total number of 1 − 3 openings was found to be most common for both windows and doors, of which the relative prevalence of 1 of each opening type was found to be highest. In addition, it was further recorded that 23/25 (92 %) households have a total number of openings within the range of 1 − 3, including both opening types, out of which a total number of 2 openings was documented as most common. In addition, the average number of kitchen openings facing outside was found to be 1.96.

Table 17: Prevalence of households having specific number of opening types facing outside.

Prevalence of households having specific number of openings		
Number of openings per household	**Number of households**	
	Windows	Doors
0	12	1
1	**10**	**17**
2	3	5
3	0	2
4	0	0
5	0	0
Total:	25	25

To summarize, given that the majority of the kitchens have at least one window and one door, that the most common number of windows and doors applied in the kitchen was found to be 1 respectively and that the most common *total* number of openings was documented to be 2, the most common opening combination in Chame is declared as 2 openings facing outside in form of 1 window and 1 door.

Opening configuration

Regarding relative opening placement of openings in the kitchen, single sided ventilation was documented for 13/25 kitchens (52 %) out of which 7 households (28 %) only have one opening facing outside. 11/25 households (44 %) were recorded to have the possibility to employ some kind of cross ventilation, where 9 kitchens (36 %) have openings placed on opposite walls and 5 kitchens (20 %) have openings placed on adjacent walls, out of which 3 kitchens (12 %) have the possibility to use both cross and side ventilation. This is further displayed in Table 18. Consequently, the majority of the kitchens is declared to have the possibility to take advantage of single sided ventilation only.

Table 18: Specification of prevalence of different types of opening configurations observed among the surveyed households.

Ventilation situation overview		
Opening configuration	**Number of households**	**Percentage of households**
Single sided ventilation	**13**	**52 %**
Single opening	7	28 %
Several openings	6	24 %
Alterntive to single sided ventilation	**11**	**44 %**
Cross	6	24 %
Side	2	8 %
Cross + side	3	12 %
No openingsfacing outside	**1**	**4 %**
Total:	**25**	100 %

Table 19 presents the number of kitchens only having *one* type of relative opening placement (no combinations of single sided, cross and/or side ventilation included). These statistics are hence valid for households having a limited number of openings only. Here it is shown that 4/25 kitchens have openings placed on opposite walls and 2/25 kitchens have openings placed on adjacent walls. 13 households were found to have access to single sided ventilation only, out of which 5 kitchens have two openings placed on the same wall. As a result, single sided ventilation was further confirmed to be the most common opening configuration for kitchens with only two openings as well. Table 19 further affirms that the most common combination of opening types for single sided ventilation of two openings is one window and one door.

Table 19: Prevalence of households with exclusive relative opening placements

Opening configurations: Exclusive ventilation possibilities		
Relative placement	**Number of households**	**Percentage of households**
Single sided (Several openings)	**13**	**52 %**
only one opening	7	28 %
window + window	0	0 %
window + door	5	20 %
door + door	0	0 %
window + window + door	1	4 %
Cross ventilation (2 openings)	**4**	**16 %**
window + window	0	0 %
window + door	2	8 %
door + door	2	8 %
Side ventilation (2 openings)	**2**	**8 %**
window + window	0	0 %
window + door	1	4 %
door + door	1	4 %

Orientation of openings

The most common orientation of windows was found to be east as confirmed by Table 20. Table 20 further suggests that south-facing outer doors were most common among the surveyed households, however with a less significant difference as portrayed by the relatively even spread among the door orientations observed.

Table 20: Prevalence of households having openings facing specific orientations.

Orientation	**Number of households (Percentage of all households)**			
Type of opening	**S**	**W**	**N**	**E**
Window	2 (8 %)	3 (12 %)	3 (12 %)	**8 (32 %)**
Door	**9 (36 %)**	8 (32 %)	8 (32 %)	8 (32 %)

Looking closer at the orientation of different opening configurations with more than one openings facing outside, Table 21 displays that single sided ventilation was most commonly observed on eastern walls. Here it can further be noted that the combination of a window and a door is the most common single sided opening configuration in case of several openings.

Table 21: Specification of orientation of single sided opening configurations and opening types observed. These statistics do not consider having cross ventilation possibilities or not. Here only the orientation of each single sided opening configuration observed is assessed.

Number of single sided opening configurations = 11	**Prevalence**			
Orientation	**S**	**W**	**N**	**E**
Window + window				1
Door + window		2	1	**7**
Door + door				
Total:		2	1	**8**

Considering the orientation of cross ventilating opening configurations, openings situated in an eastern-western direction was most commonly observed for openings placed on opposite walls as presented in Table 22. Here it is further confirmed that the most common combination of oppositely placed opening types are windows and doors.

Table 22: Specification of orientation of cross ventilating opening configurations and opening types observed. These statistics do not consider having single sided opening configurations or not. Here only the orientation of the opposite-facing openings observed is assessed.

Number of opposite placed openings = 13	**Prevalence**	
Orientation	**N - S**	**E - W**
Window + window	0	2
Door + window	2	4
Door + door	3	2
Total:	5	**8**

Opening size

Average dimensions and average area for openable windows and doors facing the outside environment are presented in Tables 23 and 24, respectively.

Table 23: Specification of average dimensions for windows and doors of different orientations.

Average dimensions / m				
	Windows		**Doors**	
Orientation	Width	Height	Width	Height
S	0,52	0,79	0,69	1,72
W	0,64	0,78	0,77	1,86
N	0,83	0,97	0,85	1,67
E	0,98	1,08	0,79	2,00
All orientations	**0,84**	**0,97**	**0,77**	**1,81**

Table 24: Specification of average opening area for windows and doors with different orientations.

Average openable area / m^2		
Orientation	**Windows**	**Doors**
S	0,42	1,18
W	0,54	1,42
N	0,72	1,42
E	1,19	1,58
All orientations	**0,92**	**1,39**

Table 25 displays that the largest total openable area (including all windows and doors observed for each orientation) was found on eastern walls, further suggesting that openable openings are most commonly placed with eastern orientation.

Table 25: Specification of total openable area documented for each orientation.

	Total openable area / m^2			
	S	**W**	**N**	**E**
Windows	0,83	1,62	1,44	10,75
Doors	10,58	11,45	11,22	12,62
Total	11,42	13,07	12,66	**23,38**

The most common architectonic features upon which the geometrical base case was created are summarized in the bullet points below.

SUMMARY

Architectonic features

- **Kitchen layout:** The majority of kitchens observed were situated on the ground floor being enclosed from other rooms.
- **Average kitchen volume:** The average kitchen volume based on average kitchen dimensions was assessed to 28 m^3.
- **Opening specification**
  - *Opening types:* The majority of the kitchens were observed to have at least one window and a door facing outside.
  - *Number of openings:* The most common number of windows and doors was 1 respectively and the most common total number of openings were 2.
  - *Relative opening placement:* Single sided ventilation was found to be the most common relative opening placement among the surveyed kitchens. The majority of the households did not have the possibility to cross ventilate. Single sided ventilation was further found to be most common when looking at kitchens with only two openings.
  - *Orientation of openings:* East-facing windows were found to be most common in terms of opening orientation. Most common orientation of doors was difficult to assess due to the relative even spread among the door orientations observed. However the largest total openable area (including both windows and doors) was found on eastern walls.

6.1.2 Specification of geometrical base case

Based on the statistical findings presented in the earlier sections, a specification of the architectonic features and physical prerequisites for natural ventilation applied in the geometrical base case model is displayed in Table 26 and 27.

Table 26: Specification of the architectonic features of the hypothetical kitchen referred to as the geometrical base case.

Architectonic features of geometrical kitchen	
Volume	28,16 m^3
Enclosed from other rooms	Yes
Type of openings	1 window + 1 door
Opening configuration	Single sided
Opening orientation	East

Table 27: Opening dimensions and total opening area of the openings applied in the geometrical base case.

Geometrical base case opening specification			
Opening type	**Width / m**	**Height / m**	**Area / m^2**
Window	0,9	0,9	0,81
Door	0,8	2	1,6
Total area			**2,41**

Selection of opening configuration

The opening configuration applied in the geometrical base case was selected according to the most common opening situation observed in the kitchens of Chame being one window and one door. Both openings were placed on the eastern wall as presented in Table 26, despite the fact that south-facing doors were found slightly more common than the other orientations. This since it was found that single sided ventilation was the most common relative opening placement, that the window-door combination showed the highest prevalence of opening combination for single sided ventilation, and that the largest total openable area was found on eastern walls. Due to rather varying dimensions among the east-facing windows, width and height were determined by standard deviation calculations comparing the two most common groups of window dimensions (see Appendix A.2.1). This explains the different window dimensions displayed in Figure 27 compared to the average dimensions presented in Figure 23. Differences in dimensions between east-facing outer doors were however not found significant hence standard deviation calculations were not considered necessary. As a result, geometrical base case outer door dimensions were based on averages of east-facing outer doors. A specification of all documented opening dimensions is found in Appendix A.2.1.

6.1.3 Household characteristics

Empirical data on the access to and usage of different stove and fuel types obtained from all 25 households serving as a base for the assessment of the current situation is presented in the following sections.

Stove type

Access

In Table 28 it can be seen that the only stove types observed in Chame were TCS, ICS and gas stoves. It is further displayed that the majority of the households (96 %) have access to an ICS, being the most common biomass fired cooking stove observed in field.

Table 28: Prevalence of households in Chame having access to specific stove types.

Type of stove	Number of households	Percentage of households
TCS	1	4 %
ICS	24	**96 %**
Gas	22	**88 %**
Electricity	0	0 %
Other	0	0 %

It was further found that 22/25 households (88 %) have access to a gas stove. However only 1 of these 22 households were exclusively reliant on a gas stove to cover daily energy needs, suggesting that the majority of the surveyed households have access to *both* an ICS and a gas stove. Figure 16 displays the relative prevalence of households having access to specific stove types and stove type combinations.

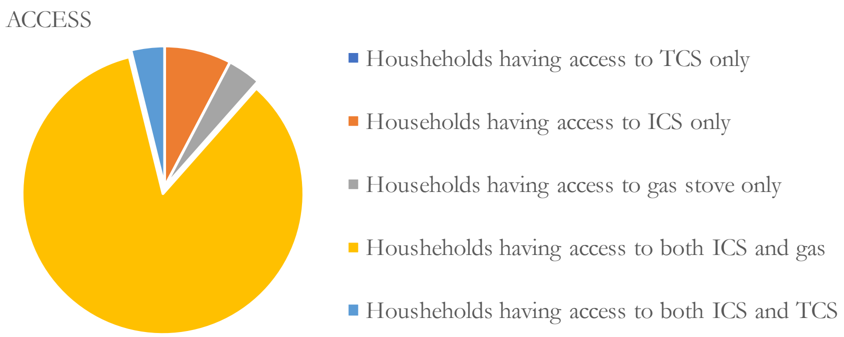

Figure 16: Relative prevalence of households having access to specific stove types.

Usage

Figure 17 specifies in which combinations the different stove types are used, displaying that biomass fired cooking stoves are used in the majority of the surveyed households. Figure 18 displays the seasonal differences between stove types used where 10/25 (40 %) of the households exclusively use gas during summer. The ICS is hence found to be the main stove used in all households both summer and winter. Figure 19 further specifies when and why gas is used among the gas-using households.

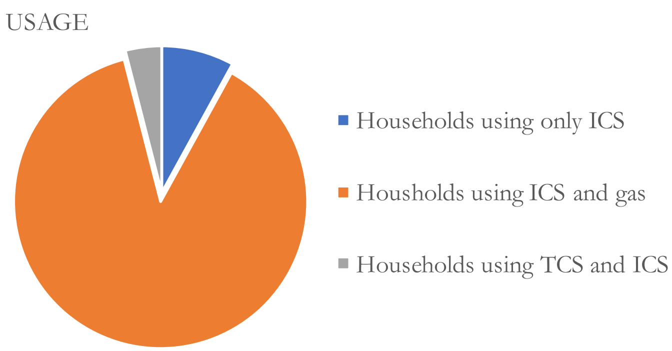

Figure 17: Specification of stove usage combinations.

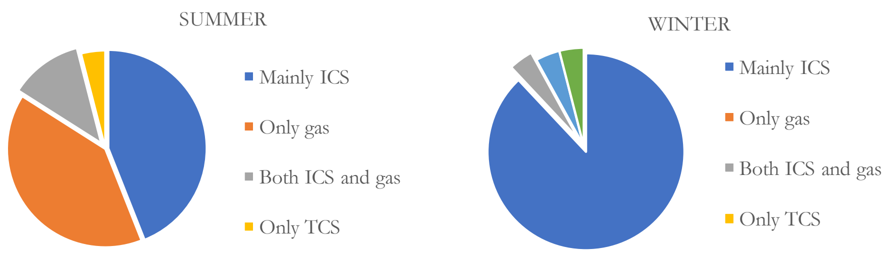

Figure 18: Specification of seasonal usage of different stove types.

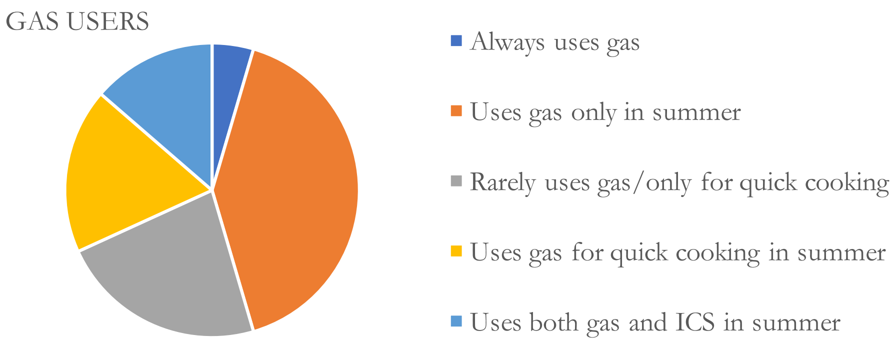

Figure 19: Specification of when and why gas is used among the households having access to a gas stove.

To summarize, Figure 16 to 19 suggest that the majority of the surveyed households in Chame are reliant on biomass fired cooking stoves to cover annual energy needs.

Additional facts

The different stove types were explained to be used for different purposes. Some households were exclusively using gas during the warmer summer months in order to avoid the excess heat that the ICS generates. However the households who did not only use gas during summer claimed to use gas only for quick cooking or "*in case of emergency*", since lighting the ICS requires more time. Some households further declared to be using the gas stove as a complement to the ICS during cooking, using both stoves simultaneously.

Fuel type

As displayed in Table 29, firewood was recorded to be the most common type of solid biomass fuel used in Chame. Since the majority of the households was found to be reliant on biomass fired cooking stoves, these results suggest that firewood is the most common type of fuel used to cover annual cooking and heating needs in Chame.

Table 29: Prevalence of households using specific fuel types.

Type of fuel	Number of households	Percentage of households
Wood	24	**96 %**
Dung	0	0 %
Agricultural waste	0	0 %
Charcoal	1	4 %
LPG	22	**88 %**
Kerosene	0	0 %
Other	0	0 %

Stove placement

A specification of placement of the ICS in the kitchen with respect to opening configuration is found in Table 30. The ICS was most commonly observed to be placed in the middle of a wall without openings, with openings situated on adjacent walls of which single sided ventilation showed the highest prevalence.

Table 30: Specification of placement of the ICS with respect to different opening configurations. Two households were excluded from these statistics: 1 with no openings facing outside and 1 only having a gas stove

Stove placement with respect to opening configuration	Number of households
Opposite openings	7
Same wall as opening	1
Openings on side wall	**9**
Between openings	6
Total:	**23**

SUMMARY

Household characteristics

- **Stove type:** The majority of the households were using an ICS as the main stove to cover annual cooking and heating needs.
- **Fuel type:** Firewood was documented to be the most commonly used fuel in Chame.
- **Stove placement:** The ICS was observed to be most commonly placed by a wall without openings, however not between cross ventilating windows.

6.1.4 Behavioral patterns

In the assessment of stove usage and ventilation patterns, three of the surveyed households were excluded. These households are further specified below followed by a justification of the exclusion:

- **1 household having a constantly opened hole in the roof:** Excluded to eliminate the possibility that the practice of actively opening openings would be influenced by the constant ventilation provided by the hole in the roof.
- **1 household migrating down to lower altitude in winter:** Excluded in order to keep the same number of households as a reference for the summer and winter statistics allowing for comparisons between seasonal behavior.
- **1 household having no openings facing outside:** Excluded since the scope of this study concerns the employment of natural ventilation through openings facing the outdoor environment.

As a result, the requirements for the households included in the stove usage and ventilation practice assessment were to be active ventilators, reside in Chame both summer and winter and to have openings facing outside. The baseline of total number of households eligible for the behavioral pattern assessments was thus reduced from 25 to 22.

Three different groups of analysis
As briefly mentioned in the method chapter, behavioral patterns for different groups of residents were analyzed dependent on stove type used and orientation of openings. Firstly, stove usage and ventilation patterns including all households were examined, that is, assessing the *general* behavior among the surveyed residents using both ICS and gas stoves in kitchens with openings of all orientations (n = 22 households). Nonetheless, since gas stoves do not generate indoor air pollutants of the same order of magnitude as biomass fired cooking stoves, stove usage and ventilation patterns for *ICS users only* (n = 12 households) were assessed to eliminate and investigate possible deviations in ventilation behavior depending on stove type used.

At last, a specific behavioral pattern assessment to be used for the IAP calculations and operative temperature simulations was conducted, valid for the geometrical base case. Hence, stove usage and ventilation patterns were assessed for the households having the following criteria: mainly using an ICS in kitchens with eastern openings (n = 5 households). This in order to eradicate eventual disparities regarding the practice of opening openings of certain orientations (e.g. due to common cold wind directions) as well as to avoid differing ventilation patterns dependent on the stove type used.

Stove usage and ventilation correlations

A specification of stove usage and ventilation activities for the surveyed group of households representing the geometrical base case and using ICS as a main stove both summer and winter is presented in Table 31 − 34. Similar tables displaying behavioral patterns for the *General* case including all households as well as for *ICS users only* are provided in Appendix A.2.4.

Overview of stove usage and ventilation practices: Summer

Table 31 displays that the majority of the households use the stove both morning and afternoon during summer (80 % and 100 % respectively). All households who use the stove have openings opened during stove usage activity, both morning and afternoon. No households have openings opened *only* when the stove is not used. However, the majority of the households (75 %) also keep openings opened between morning and evening stove usage.

Table 31: Specification of stove usage and ventilation practices and their inter-correlation during summer.

ICS users with eastern openings	SUMMER		
Total number of households = 5	MORNING	AFTERNOON	WHOLE DAY
Number of households using their stove	4/5 (80 %)	5/5 (100 %)	0
Number of households who use the stove but do not open openings	0	0	
Number of households who open openings when not using the stove	0	0	
Number of housholds who neither use the stove nor open openings	1/5 (20 %)	0	
Number of households who open openings when stove is used	4/4 (100 %)	5/5 (100 %)	
Only during stove usage	1/4 (25%)	2/5 (40 %)	
During stove usage and whole day	3/4 (75 %)	3/5 (60 %)	

Stove usage and ventilation correlations: point in time

Table 32 displays that all households who actively open openings during stove usage open openings the same time as the stove is lit in the morning (100 %). If not ventilating all day, all households who use the stove in the afternoon open openings at the time when the stove is lit as well (40 %). Hence, no households actively open openings in between stove usage activity.

Regarding the practice of closing openings, all households who ventilate during morning stove usage and do not keep openings opened all day, close openings when the stove is extinguished (25 %). Furthermore, no households keep openings opened *after* the stove is extinguished in the evening. Rather, if not closing openings at the time when finishing stove usage activity (80 %), openings were closed *before* the stove was extinguished (20 %).

Table 32: Specification of stove usage and ventilation practices and their intercorrelation considering point in time and duration of each activity during summer.

ICS users with eastern openings	**SUMMER**	
Total number of households = 5	MORNING	AFTERNOON
Number of households using stove and open openings during stove usage	4/5 (80 %)	5/5 (100 %)
Opening openings		
Openings opened when stove is lit	4/4 (100 %)	2/5 (40 %)
Openings opened during stove usage	0	0
All day ventlilators		3/5 (60 %)
Closing openings		
When stove is exinguished	1/4 (25 %)	4/5 (80 %)
Before stove is extinguished	0	1/5 (20 %)
After stove is extinguished	0	0
All day ventlilators	3/4 (75 %)	

Overview of stove usage and ventilation practices: Winter

As in the case for summer, the majority of the households use the stove both morning and afternoon during winter (100 % and 80 % respectively) as displayed in Table 33. The seasonal difference in prevalence of households using the stove morning and afternoon lies in the fact that one household only uses the stove once a day: in the afternoon during summer and in the morning during winter. Two households have the stove lit all day (40 %) and all households who use the stove have openings opened during stove usage activity (100 %). No households have openings opened *only* between morning and afternoon stove usage, similar as was found for summer. However in winter only 40 % of the households keep openings opened the whole day (compared to 75 % in summer), corresponding to the households who also kept the stove lit all day.

Table 33: Specification of stove usage and ventilation practices and their inter-correlation during winter.

ICS users with eastern openings		**WINTER**	
Total number of households = 5	MORNING	AFTERNOON	WHOLE DAY
Number of households using their stove	5/5 (100 %)	4/5 (80 %)	2/5 (40%)
Number of households who use the stove but do not open openings	0	0	0
Number of households who open openings when not using the stove	0	0	0
Number of housholds who neither use the stove nor open openings	0	1/5 (20 %)	
Number of households who open openings when stove is used	5/5 (100 %)	4/4 (100 %)	
Only during stove usage	3/5 (60 %)	2/4 (50 %)	
During stove usage and whole day	2/5 (40 %)	2/4 (50 %)	
Number of households who have the stove lit all day			2/5 (40 %)
of which keep opening opened the whole time			2/2 (100 %)
of which keep openings opened part of the time			0

Stove usage and ventilation correlations: point in time

Table 34 displays that all households who actively open openings during stove usage open openings the same time as the stove is lit in the morning (100 %). The households who do not have the stove lit all day and hence ventilate all day (50 %), open openings the same time as the stove is lit in the afternoon as well (50 %). Hence, no households actively open openings in between stove usage activity.

Regarding the practice of closing openings, 60 % of the households who ventilate during morning stove usage close openings when stove is extinguished (compared to 25 % in summer). This is due to the fact that less households keep openings opened all day during winter. As mentioned above, the households doing so also keep the stove lit throughout the day. When it comes to evening stove usage, all households (100 %) close openings at the time as when the stove is extinguished.

Table 34: Specification of stove usage and ventilation practices and their inter-correlation considering point in time and duration of each activity during winter.

ICS users with eastern openings	**WINTER**	
Total number of households = 5	MORNING	AFTERNOON
Number of households using stove and open openings during stove usage	5/5 (100 %)	4/5 (80 %)
Opening openings		
Openings opened when stove is lit	5/5 (100 %)	2/4 (50 %)
Openings opened during stove usage	0	0
All day ventlilators		2/4 (50 %)
of which are all day stove users		2/2 (100 %)
Closing openings		
When stove is exinguished	3/5 (60 %)	4/4 (100 %)
Before stove is extinguished	0	0
After stove is extinguished	0	0
All day ventlilators	2/5 (40 %)	
of which all day stove users	2/2 (100 %)	

SUMMARY

Behavioral practices

General stove usage and ventilation practices

- The majority of households use the stove both morning and evening both summer and winter.
- All households who use the stove employ natural ventilation during stove usage activity both summer and winter.

Stove usage and ventilation correlation

- All households using the stove open openings at the same time as lighting the stove, both in the morning and in the evening, if not having openings opened all day.
- No households keep openings opened after stove usage activity in the evening. Rather, if not closing openings at the time when the stove is extinguished, openings were closed *before* stove usage was activity finished. This occurred in summer only.

Seasonal differences

- In summer 75 % of the surveyed households keep openings opened between morning and afternoon stove usage activity, whereas only 40 % do so in winter.
- In summer no households have the stove lit the whole day, whereas during winter 40 % of the households keep the stove lit throughout the day.

Stove usage and ventilation profiles

Stove usage patterns and profiles

Figure 20 presents seasonal stove usage patterns recorded for the group of households representing the geometrical base case.

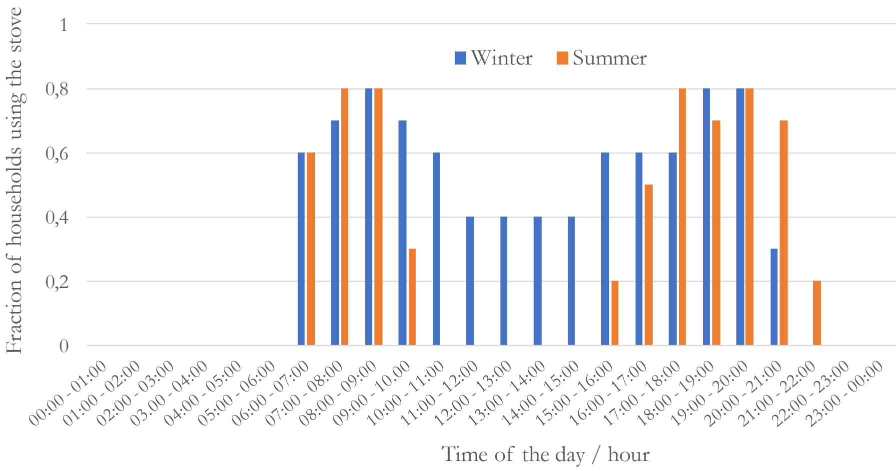

Figure 20: Seasonal stove usage patterns displaying the percentage of households using the stove a certain hour.

The documented stove usage practices display the general tendency of having the stove lit more often in winter than in summer, indicating that stoves are used for heating purposes. It can further be noted that there is a seasonal shift in common practice of afternoon stove usage patterns, where stoves are lit and extinguished earlier in winter.

Figure 21 presents the seasonal stove usage profiles derived from Figure 20, representing the stove usage practices employed in further simulations. Seasonal differences found in the assessment of the general stove usage practices are reflected as two hours longer stove usage in the morning and one hour longer stove usage in the afternoon during winter, including a shift towards earlier ignition in winter (see section 5.1.6 for details on the creation of profiles).

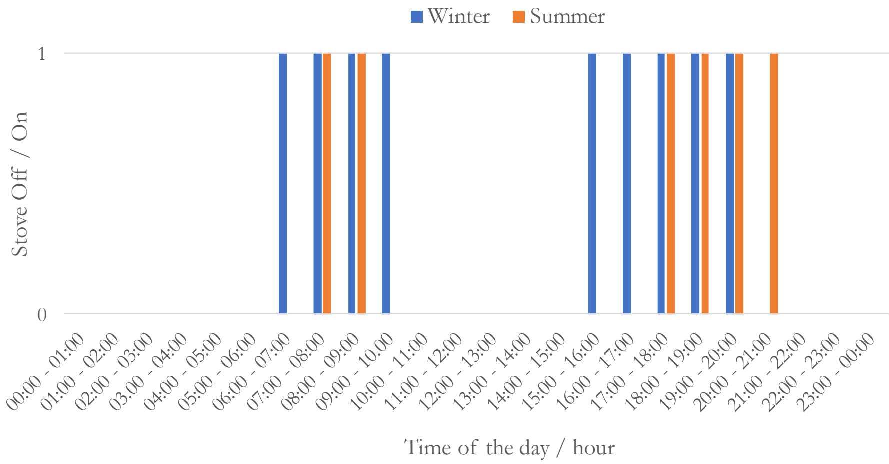

Figure 21: Seasonal stove usage profiles used in further simulations representing behavioral practices considering duration and point in time of using the stove.

Similar stove usage patterns and profiles valid for the larger groups of surveyed households (the *General* case including 22 households as well as households *Only using ICS* including 12 households) can be found in Appendix A.2.5. No large deviations between stove usage practices or profiles for the three different groups were found, serving as a validation of the representativeness of the rather limited number of households being used for further calculations and simulations.

Summer profiles derived from stove usage practices for all households as well as the group of households only using ICS showed to have the same total number of hours of stove usage activity of 6 hours as the exclusive number of households founding the geometrical base case presented in Figure 21. However, morning and afternoon stove usage were distributed slightly different over the day, where the profile for all households and for ICS users only were allocated 3 + 3 hours rather than 2 + 4 hours as presented in Figure 21. The point in time of having the stove lit was nonetheless found to be occurring on similar times of the day, and identical for the general case as well as for ICS users only.

When it comes to winter, the total number of hours of stove usage activity for all ICS users were found to be one hour less than what is presented in Figure 21 (8 hours compared to 9 hours), displayed as one more hour of stove usage in the morning. Otherwise afternoon stove usage practices were identical both in terms of duration and point in time of the day. Winter profiles based on all households resulted in two hours less stove usage per day compared to Figure 21, attributed to one hour less stove usage both in the morning and afternoon (7 hours in total). Considering seasonal differences in stove usage practice, it was found more common to keep the stove lit the whole day during winter also for the larger groups of surveyed households.

Ventilation patterns and profiles

Figure 22 presents seasonal ventilation patterns recorded for the group of households representing the geometrical base case.

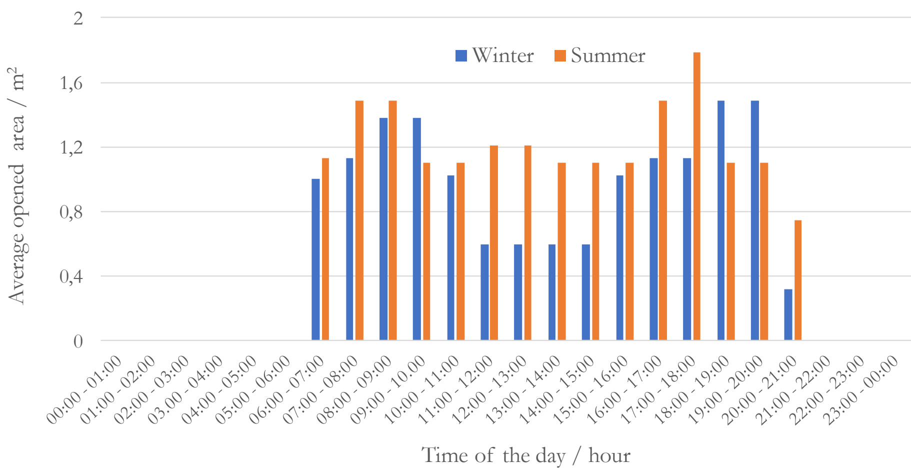

Figure 22: Seasonal ventilation patterns displaying average area opened per hour.

Figure 22 suggests that the employment of natural ventilation during winter is somewhat restrained compared to summer in terms of total area opened per hour throughout the day. It can be seen that the distribution of opened area is more homogeneous during the day in summer than in winter, illustrated as a more rectangular shape compared to winter where the total opened area more clearly follows the pattern of when the stove is used. As a result, the largest seasonal difference in opened area is concentrated to the hours between morning and afternoon stove usage activity, indicating that keeping openings opened the whole day is less common during winter compared to summer.

Figure 23 presents the seasonal ventilation profiles derived from Figure 22, representing the ventilation practices employed in further simulations. The seasonal difference in opened area identified in the general ventilation practice assessment is reflected by a reduction of average opened area of 0.24 m^2 per hour in winter. In line with the winter stove usage profile, the winter ventilation profile is shifted to an earlier start and end compared to summer.

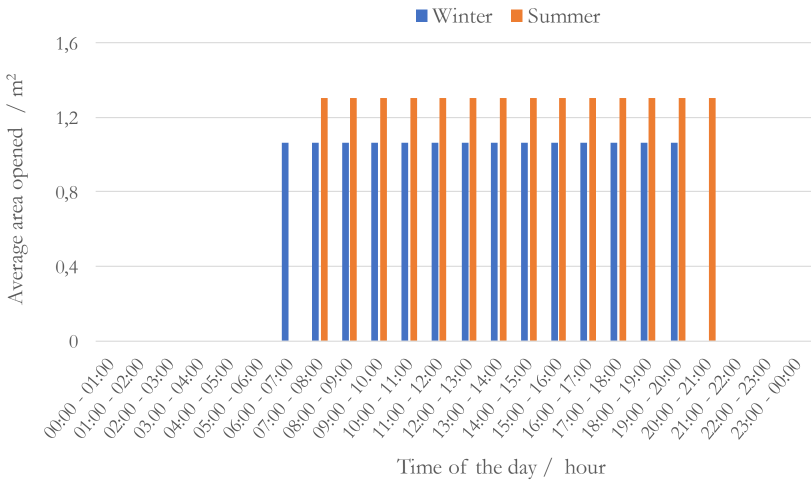

Figure 23: Seasonal ventilation profiles used in further simulations representing daily practice of employing natural ventilation considering opened area per hour.

Similar ventilation profiles valid for the larger groups of surveyed households (the *General* case including 22 households as well as the 12 households representing *ICS users only*) can be found in Appendix A.2.6. No large deviations were found between the ventilation practices for the different groups in terms of temporal employment of natural ventilation during the day, serving as a validation of the representativeness of the rather limited number of households being used for further calculations and simulations.

Point in time and duration of keeping openings opened were found identical in summer and winter for the general case as well as for ICS users only, corresponding to the winter profile presented in Figure 23 (06.00 - 20.00). However, the summer profile representing the households basing the geometrical base case were shifted towards opening and closing openings one hour later (07.00 - 21.00) compared to the summer profiles assessed for the larger groups of households.

Profiles for all three statistical groups further display the tendency to open a larger area in summer. The average opened area presented in Figure 23 was found to be in the similar range as for the profile including all households, for which the opened area was assessed to 1.24 m^2 and 1.16 m^2 in summer and winter respectively. However this seasonal difference of 0.08 m^2 is more modest than what was found for the profile presented in Figure 23 of 0.24 m^2. The profiles valid for ICS users only were shown to have significantly larger area opened both summer and winter amounting to 1.56 m^2 and 1.39 m^2 respectively, with a seasonal difference of 0.17 m^2 in opened area more similar to the area difference presented in Figure 23.

Further investigation of potential impacts on ventilation habits depending on stove type used can be made in Appendix A.2.5 and A.2.6 where behavioral practices and profiles for the households representing the *General* case including gas users and the households representing *ICS users only* are provided. Key findings of a more thorough comparison are however presented below.

Comparison General case vs. ICS users only

Stove usage practice

- Both groups have similar stove usage patterns both summer and winter.

  ⇒ Identical stove usage profiles in summer.

  ⇒ *ICS users only* use the stove 1 hour longer in winter (start earlier in the afternoon).

Ventilation practice

- Both groups have identical ventilation profiles when it comes to point in time and duration of keeping openings opened.

- *ICS users only* generally open larger area when opening openings, resulting in a specific area difference of 0.32 m^2 in summer and 0.23 m^2 in winter when comparing with the average opened area assessed for the *General* case including households also using gas.

Additional facts

In a discussion with all households regarding the reasoning behind occasionally keeping openings closed, the general explanation was to prevent insects to come inside in summer and to limit heat losses during winter. This is in line with Cowlin (2005)'s statement on that employing natural ventilation might not be suitable everywhere due to weather, privacy, pest control etc. Moreover, in the ventilation assessment for the *General* case, 2/22 (9 %) of the households did not ventilate at all during ICS stove usage in winter. Furthermore, one of these households only ventilated *between* morning and afternoon stove usage in summer. This since the respondent claimed that smoke accumulation during ICS stove usage was "not considered as a big problem", hence that opening openings during the day was to let in fresh air of no particular reason.

6.1.5 Presentation of opening configuration cases

In the following section a specification of the three opening configuration cases of investigation developed from the architectonic features of the geometrical base case and the ventilation practice assessment is provided. A graphical display of the different cases is shown in Figure 24 for which relative opening placement and opening dimensions are specified in Table 35.

1. **Current ventilation situation (Base case): Opened area**
   Compared to the geometrical base case, the actual opened area in the summer and winter ventilation profiles corresponds to 54 % as well as 44 % of the total *openable* area, respectively. Hence, the physical model aiming to represent the current situation was adapted accordingly by modifying the width of both the window and door as presented in section 5.1.7. The seasonal difference of opened area of 0.24 m^2 did however not result in unprecedented differences in opening widths in the area modification calculations for the summer and winter models. For simplicity the adjusted opening widths were rounded off to one decimal resulting in the same seasonal opening dimensions (see Appendix A.2.2). Hence, the same physical model was used for summer and winter simulations.

2. **Improved case 1: Increase of opened area**
   Given that the opening area of the geometrical base case corresponds to approximately double the size of the area representing the current ventilation situation, the original opening dimensions of the geometrical base case were applied to the physical model referred to as the improved case with *increased opened area*.

3. **Improved case 2: Employment of cross ventilation**
   As displayed in Table 18 in section 6.1.1, 44 % of the households had access to employ some kind of cross ventilation, including openings placed on adjacent walls. However, openings placed on opposite facing walls were only observed for 9/25 (36 %) of the surveyed kitchens. Moreover, when further scrutinizing present ventilation opportunities and behavior among the households included in the behavioral assessment, only 62 % and 50 % actually took advantage of the opportunity to cross ventilate in summer and winter respectively (see Appendix A.2.3). Hence, cross ventilation was confirmed to be an improved case considering type of opening configuration as well as behavioral practices representing the current ventilation situation. As a result, a window of equal size as the eastern window present in the physical model of the base case was placed on the western wall of the cross

ventilation physical model, as displayed as the opening C in Figure 24. DEROB only considers the total opened area of an opening applied on a wall in the physical model, thus the placement of the cross ventilating window on the western wall relative the situation of the eastern openings does not impact the resulting airflow rates through the building envelope or the operative temperature simulations.

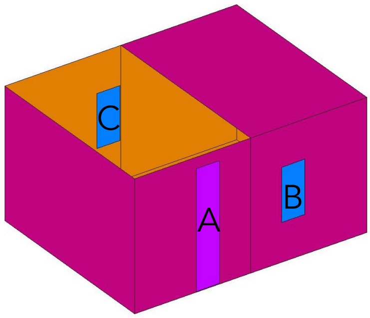

Figure 24: Graphical display of the physical models used in the simulation tool DEROB. Dimensions of each opening (A, B and C) and total opened area are specified for the each opening configuration case in Table 35.

Table 35: Specification of opening dimensions and total opened area for each opening configuration case. A, B and C correspond to the openings illustrated in Figure 24.

Opening dimensions and total area				
Opening configuration	**A**	**B**	**C**	**Total area**
Base case	0.4 m · 2 m	0.4 m · 0.9 m	-	1.16 m^2
Increased opened area	0.8 m · 2 m	0.9 m · 0.9 m	-	2.41 m^2
Cross ventilation	0.8 m · 2 m	0.4 m · 0.9 m	0.4 m · 0.9 m	1.52 m^2

6.1.6 General observations

Observations of importance made during the field study justifying the selection of input parameters for the IAP calculations and operative temperature simulations are presented below.

Stove usage practices

- Despite the presence of an ICS fitted with chimney there was still a considerable amount of smoke in the kitchen as seen in Figure 25a, an observation in line with what was found in Parajuli, H. Lee, and K. Shrestha (2016)'s investigation of ICS performance in rural mountainous households in Nepal. Furthermore, in a comparative study of TCS and ICS conducted by Singh et al. (2012), over 75 % of ICS users reported on smoke accumulation in the kitchen. Nepal Energy Efficiency Programme (NEEP) further confirms that the practical performance of an ICS is still much less in field than what has been shown during ideal conditions (Nepal Energy Efficiency Programme (NEEP) 2011).
- The ICS were used improperly. Singh et al. (2012) suggests that cultural practices may influence the performance of an ICS and resulting IAP levels, a statement which supports the observations made in Chame: long wooden sticks were sticking out from the combustion chamber, blocking the fire gate to be kept closed (if there even was a gate), hindering an enclosed combustion process. As a result, smoke was directly emitted into the indoor environment both from the combustion chamber as well as from the wood combustion taking place outside the stove creating what was similar to an open fire scenario (see Figure 25). Not cutting the firewood before feeding the combustion chamber was explained by the Nepali research team as a remnant from previous habits when cooking on open fire or TCS. Metering of fuel by gradually pushing it into the fire is employed in order to conserve fuel since only the tip of the wood is burned, as also is confirmed by Still et al. (2011).

(a) Combustion of firewood taking place outside the combustion chamber.

(b) Firewood logs gradually metered into the fire.

Figure 25: Stove usage activity in two of the surveyed kitchens in Chame.

- Lack of proper fuel preparation was observed. Few people were drying their wood on top of the stove before use. The moisture content of fuel wood has an impact on the resulting combustion efficiency (see chapter 3: *Theory*), hence has a direct influence on the magnitude of pollutants generated during the combustion process from incomplete combustion.

- Smoke was entering the indoor environment from badly fitting pots. In some of the households which were cooking at the point in time of survey, it was confirmed that smoke from the pot holes was contributing to the overall fugitive emissions associated with the ICS as displayed in Figure 25a.

6.2 IAP assessment

6.2.1 Airflow rate calculations

Weighted averages of airflow rates generated by the different opening configuration cases are summarized in Table 36 together with the resulting air exchange rates (AER) calculated according to Equation 1.

Table 36: Annual weighted averages of airflow rates for each opening configuration case and correlated AER used in the single zone model assessing the indoor concentrations of CO during stove usage activity.

Opening configuration case	Airflow rate Q / (l/s)	AER / h^{-1}
Current situation	217	28
Increase of opened area	356	46
Cross ventilation	451	58

Table 36 displays that a larger opening area as well as taking advantage of cross ventilation result in a significant increase of airflow rates through the building envelope compared to the base case. Increasing the opened area of single sided ventilation with around 100 % result in a 60 % higher AER whereas applying a window of same size on the opposite facing wall correspond to an increase in AER with over 100 %.

6.2.2 Indoor concentrations of CO

Role of fugitive emissions

Indoor concentrations of CO during and after operation of a wood-fired cooking stove resulting from different levels of fugitive emissions and the ventilation rates presented in Table 36 are summarized in Table 37 and put in relation to IAQ guideline values in the case-specific Tables 38, 39 and 40. This in order to demonstrate the relative impact of the selection of chimney reduction potential on the resulting indoor CO levels. All CO concentrations presented are based on the same stove usage and ventilation profiles in terms of point in time and duration of each activity. As a result, indoor concentrations of CO resulting from the two improved cases display the relative impact of different opening configuration designs on indoor air pollution levels rather than modified behavioral patterns.

Table 37: Mean concentrations of CO in g/m^3 averaged over 1 hour for all opening configuration cases and chimney reduction potentials of 30 %, 69 % and 90 %.

Mean concentration of CO / (g/m^3)				
Opening configuration	**No chimney**	**30 %**	**69 %**	**90 %**
Base case	0.219	0.153	0.067	0.022
Increased opened area	0.135	0.094	0.041	0.014
Cross ventilation	0.107	0.074	0.033	0.011

Table 38: Specification of resulting indoor concentrations of CO for the *base case* representing the current ventilation situation put in relation to IAQ guidelines formulated by WHO and the Nepalese government.

Base case: Times exceeding guideline values				
Guidelines	**No chimney**	**30 %**	**69 %**	**90 %**
WHO 1 hr	6.3	4.4	1.9	0.63
Nepalese 1 hr	5.5	3.8	1.7	0.55
WHO/Nepalese 8 hrs	21.9	15.3	6.7	2.2

Table 39: Specification of resulting indoor concentrations of CO for the improved case with an *increased opened area* of single sided ventilation with around 100 %, put in relation to IAQ guidelines formulated by WHO and the Nepalese government.

Increased opened area: Times exceeding guideline values				
Guidelines	**No chimney**	**30 %**	**69 %**	**90 %**
WHO 1 hr	3.9	2.7	1.2	0.39
Nepalese 1 hr	3.4	2.4	1.04	0.34
WHO/Nepalese 8 hrs	13.5	9.4	4.1	1.4

Table 40: Specification of resulting indoor concentrations of CO for the improved case with an additional window applied to the opposite facing wall providing *cross ventilation*, put in relation to IAQ guidelines formulated by WHO and the Nepalese government.

Cross ventilation: Times exceeding guideline values				
Guidelines	**No chimney**	**30 %**	**69 %**	**90 %**
WHO 1 hr	3.0	2.1	0.94	0.31
Nepalese 1 hr	2.7	1.9	0.82	0.27
WHO/Nepalese 8 hrs	10.7	7.4	3.3	1.1

Table 37, 38, 39 and 40 display that indoor levels of CO is a direct result of chimney reduction potential representing the level of fugitive emissions entering the indoor environment as well as AER. Except from the case of cross ventilation with a chimney reduction potential of 69 % (highlighted as green cells in Table 37 and 40), indoor concentrations only reach safe levels with respect to 1 hour guideline values if the presence of a chimney vents out 90 % of the CO generated by the combustion of wood in the combustion chamber. However, indoor CO levels for all opening configuration cases and chimney reduction potentials examined in this study exceed 8 hour guideline values as displayed in Table 38, 39 and 40.

Ventilation efficiency of different cases

Further analysis of the ventilation efficiency provided by different opening configurations will be limited to one of the chimney reduction potentials investigated. A reduction of indoor fugitive emissions with 69 % was selected under the pretext that this figure is derived from an hourly assessment of indoor CO levels hence considered to be most applicable to the calculations performed in this study. As a result, Figure 26 displays indoor concentrations of CO resulting from all opening configuration cases valid for a chimney reduction potential of 69 %, extracted from the highlighted cells of green and yellow in Table 37, 38, 39 and 40.

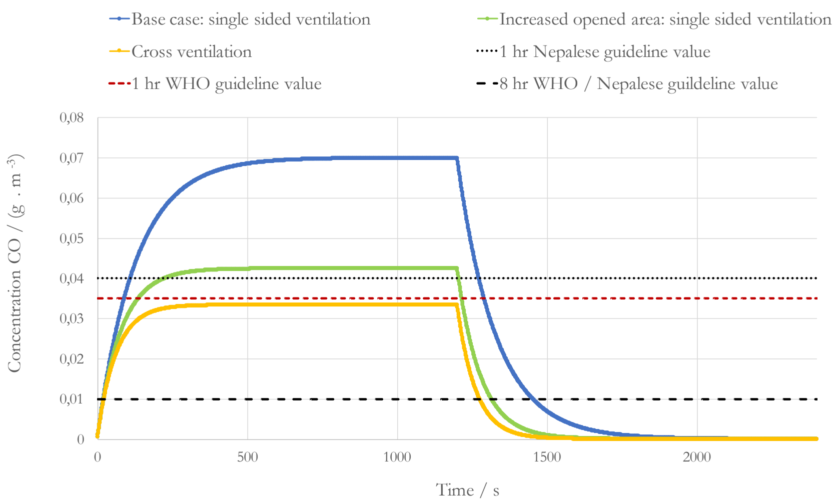

Figure 26: Indoor concentrations of CO resulting from the different opening configurations cases valid for a chimney reduction potential of 69 % and based on airflow rates presented in Table 36.

Figure 26 confirms that increased airflow rates induced by natural ventilation result in an increased ventilation efficiency with respect to the ability to reduce indoor concentrations of CO generated by wood-fired cooking stoves. Peak concentrations of CO were found for the base case representing the current scenario, exceeding WHO 1 hour IAQ guideline values with around a factor of 2. Increasing the opened area and employing cross ventilation show to decrease indoor concentrations of CO with 39 % and 51 % respectively (see Table 37 for exact concentrations). Nonetheless, only the case of cross ventilation ensure indoor CO levels below safe limits considering both WHO IAQ guidelines and the Nepalese standard for 1 hour exposure (hence highlighted as a green colored cell in Table 37). Doubling the area of single sided ventilation still exceed permissible values formulated by WHO with 20 %, however only slightly passes the guideline value stated in the Nepalese standard as presented in Table 39.

Figure 26 further displays that steady state peak concentrations are reached faster the larger ventilation efficiency. The rate at which CO is vented outside after the stove is extinguished suggest that the required opening time in order to reach IAQ guidelines is within the range of a couple of minutes for all cases, given the present assumptions on a completely homogeneous air mixture.

6.3 Operative temperature assessment

The impact of ventilation efficiency on indoor thermal comfort is assessed in the following section. This by presenting annual distribution as well as annual frequency of indoor operative temperatures (T_{op}) resulting from each opening configuration case, based on the same local climate conditions and behavioral patterns considering stove usage and ventilation practices. Diurnal dynamics of T_{op} are further displayed in order to highlight the impact of current stove usage and ventilation patterns on indoor thermal comfort.

6.3.1 Annual distribution of T_{op}

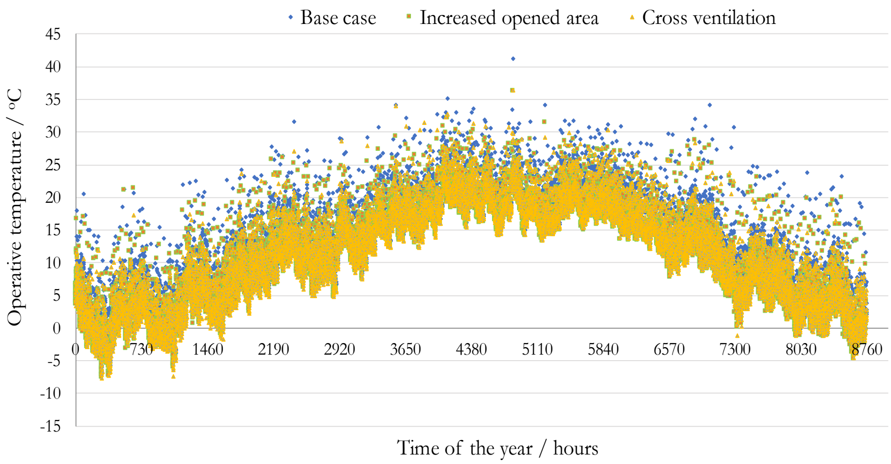

Figure 27: Distribution of indoor operative temperatures (T_{op}) over the hours of the year for all opening configuration cases.

Figure 27 outlines the annual distribution of T_{op} for the different opening configuration cases. It can be seen that the higher airflow rates provided by the improved cases result in generally lower T_{op} than the base case. Nonetheless, Figure 27 displays that there is a wide distribution of T_{op} throughout the year for all opening configuration cases. The prominent seasonal dependence indicates that indoor thermal comfort is strongly influenced by the surrounding climate.

6.3.2 Annual frequencies of T_{op}

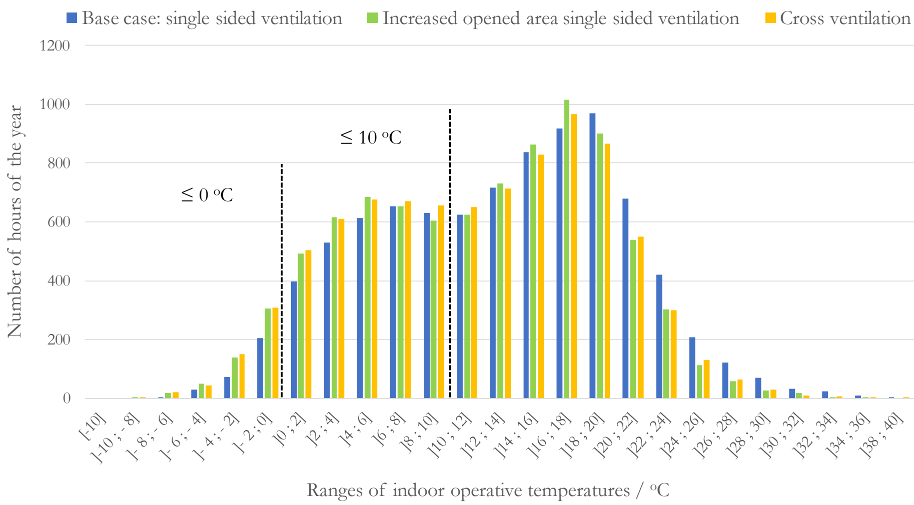

Figure 28: Histogram displaying annual prevalence of indoor operative temperatures categorized in different temperature ranges for all opening configuration cases. Total number of hours of T_{op} falling below 10 ^{o}C and 0 ^{o}C are highlighted as a measure on thermal *dis*comfort.

Figure 28 quantifies the impact of an increased ventilation efficiency on indoor thermal comfort by summarizing the annual prevalence of specific T_{op} ranges for the kitchens with different opening configurations. It is shown that most common indoor operative temperatures for the base case fall within the range of 18 ^{o}C to 20 ^{o}C whereas temperatures between 16 ^{o}C to 18 ^{o}C are displayed as most common for the opening configuration cases providing higher ventilation rates. Yet it is shown that T_{op} fall below 0 ^{o}C and 10 ^{o}C for a substantial part of the year for all opening configuration cases. Figure 27 further suggests that indoor operative temperatures below 0 ^{o}C most commonly occurs from December through February. Increased airflow rates are however displayed to result in higher frequencies of lower temperatures as further specified in Tables 41 and 42.

Thermal discomfort

The annual prevalence of hours and corresponding time in days with indoor operative temperatures below 10 ^{o}C and 0 ^{o}C are summarized for all opening configuration cases in Table 41 and 42, respectively.

Table 41: Annual prevalence of hours, days and corresponding percentage of the year when T_{op} are or fall below 10 ^{o}C.

Annual prevalence of T_{op}: $\leq$ 10 ^{o}C			
Opening configuration	**Hours**	**Days**	**Percentage of the year**
Current situation	3 128	130.3	35.7 %
Openable area	3 561	148.4	40.7 %
Cross ventilation	3 643	151.8	41.6 %

Table 42: Annual prevalence of hours, days and corresponding percentage of the year when T_{op} are or fall below 0 ^{o}C.

Annual prevalence of T_{op}: $\leq$ 0 ^{o}C			
Opening configuration	**Hours**	**Days**	**Percentage of the year**
Current situation	307	12.8	3.5 %
Openable area	510	21.2	5.8 %
Cross ventilation	526	21.9	6.0 %

6.3.3 Diurnal dynamics of T_{op} for summer and winter

Daily fluctuations of indoor operative temperatures for all opening configuration cases are displayed for one day in summer and one day in winter in Figure 29 and 30. This in order to highlight the diurnal dynamics of T_{op} resulting from stove usage and ventilation patterns in different seasons.

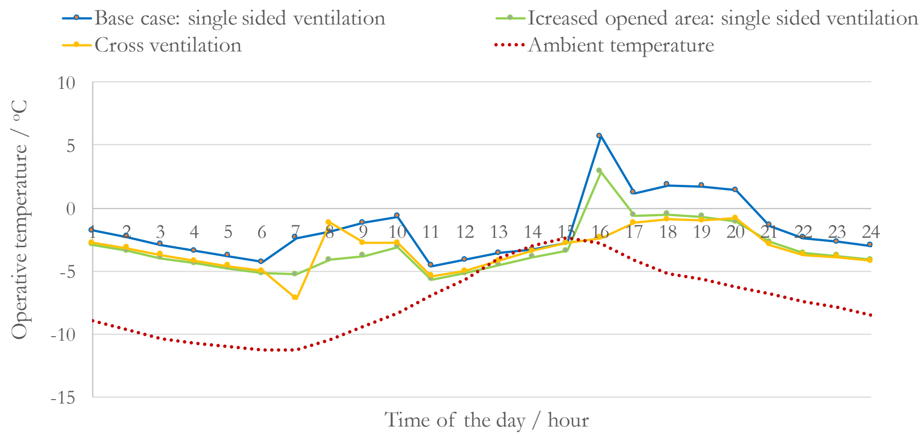

Figure 29: Example of diurnal fluctuations of indoor operative temperatures (T_{op}) resulting from different opening configurations in winter: 15th of January.

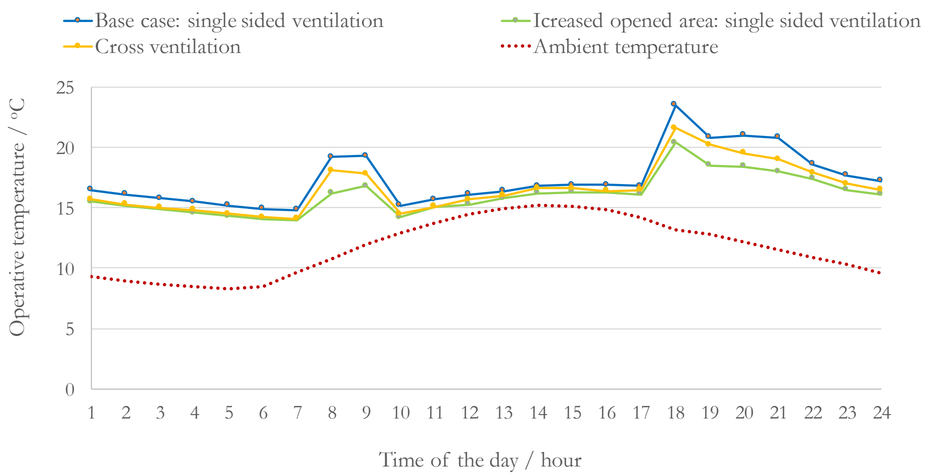

Figure 30: Example of diurnal fluctuations of indoor operative temperatures (T_{op}) resulting from different opening configurations in summer: 15th of July.

Peaks and declines of the graphs displayed in Figure 29 and 30 show that both stove usage and ventilation practices have an impact on the diurnal dynamics of indoor operative temperatures in summer as well as in winter. The rapid decrease in T_{op} observed between 10.00 am - 11.00 am in winter and 09.00 am - 10.00 am in summer result from keeping openings opened after the stove is extinguished in the morning. However, it is further shown that T_{op} decreases with the same rate as the ambient temperature after the stove is extinguished and openings are closed at night, indicating that the performance of the house construction in preserving the heat generated by the stove is insufficient.

Fluctuating values such as sudden drops followed by instant inclines visualize that the dynamics of the surrounding climate has a prominent influence on indoor T_{op}. This since changes in wind speed, wind direction, ambient temperature and incoming solar radiation all have an impact on the airflow rates through the building envelope in DEROB. The case of cross ventilation showed the most prominent fluctuations as exemplified between 06.00 am and 08.00 am in Figure 29, suggesting that indoor thermal comfort in kitchens with cross ventilation is subject to a higher level of influence by changes in local climatic conditions.

Nonetheless, other parameters such as heat storage in the building materials resulting from the influence of solar radiation also have an impact on indoor thermal comfort. The fact that T_{op} for all cases reach the highest temperatures during afternoon stove usage in winter can be explained by the synergistic effect of a stronger solar irradiation on the building envelope at that time of the day. However, the incline of T_{op} is not as marked in the kitchen with cross ventilation as for the kitchens with single sided ventilation. This due to the accelerated air exchange rate resulting from temporary high wind speeds, again portraying the pronounced influence of wind-related weather characteristics on indoor thermal comfort in the kitchen with cross ventilation.

Regarding the indoor thermal climate in winter presented for January 15th, operative temperatures are not kept above 5 ^{o}C for any case and coincide with ambient temperatures after morning stove usage as presented in Figure 29. This occurs around mid day after the stove is extinguished in the morning and openings are kept opened, suggesting that all opening configurations generate airflow rates which exchange *all* indoor air after a certain time.

A larger difference between indoor operative temperature and ambient temperature can be seen for July 15th representing summer climatic conditions. This is attributed to the magnitude of incoming solar radiation which in combination with the radiant heat generated by the stove meet the thermal capacity of the construction materials resulting in heat storage in the building envelope. Figure

30 further displays that T_{op} during stove usage is higher in the kitchen with cross ventilation than the improved case with single sided ventilation. This can both be explained by additional heat gains generated by the influence of solar radiation on the west-facing cross ventilating window as well as temporary low wind speeds. July 15th hence represent a scenario of when ventilation rates induced by stack effect overrides wind-driven cross ventilation rates in case of low wind speeds and large temperature differences between indoor and outdoor air.

7 DISCUSSION

The discussion of this thesis is divided in two main parts. Firstly, the findings from each research step will be commented and discussed separately in chronological order as presented in the *Results* chapter. Secondly, a synthesis and evaluation of the correlation between ventilation rates, IAP levels and indoor thermal climate will be provided, followed by a holistic outlook on how the concept of sustainability can be applied to the trade-off between IAP and thermal comfort. This as a prelude to the conclusions presented in the final chapter where the research questions are explicitly answered.

7.1 Interview study

7.1.1 Architectonic features and bioclimatic design

Building layout and construction materials

The documented architectonic features of the surveyed households in Chame deviate from the suggested bioclimatic design strategies presented by Bodach, Lang, and Hamhaber (2014) for cool temperate climates when it comes to building layout and placement of the kitchen (see chapter 2.4.1: *Background*). Even if most of the dwelling units consisted of several rooms, the majority of the kitchens investigated were constructed as a separate part of the residential unit. As a result, the internal heat generated by the stove was not utilized to warm up the rest of the living area. For the limited number of respondents who lived in a house with several floors, the kitchen of only 1 household was observed to be on the ground floor within the same building envelope.

Considering general observations of construction materials, facades of wooden planks and roofs of corrugated steel were common among the surveyed kitchens in more simple house constructions as well as in more recent developed clusters of settlements as displayed in Figure 31b, 33 and 34b. However, two-storied buildings with thick stone foundations were found to be common architectural features of older houses in Chame as displayed in Figure 34a, corresponding better to the bioclimatic design strategies suggested for high altitude regions (Bodach, Lang, and Hamhaber 2014). This further confirms that more recent and "modern" building techniques risk to compromise the climate responsive design employed in vernacular architecture in highland and remote areas of Nepal as suggested by Boch-Isaacson and Dobereiner (1987).

Thus, given the hardships in finding residential respondents at the time of survey, the houses represented in the sample selection might not reflect the archetypal vernacular architecture of settlements in Chame. However, many of the households included in this research residing in either more modern or simple wooden house constructions still had the kitchen as a separate unit on the courtyard. Since the focus in this study is the architectonic features of the kitchen, a comprehensive analysis of the architectonic features of residential housing units is left for further studies.

Nonetheless, clear cut characteristics for typical architectural features for the village of Chame in line with *either* cool temperate *or* alpine climate responsive design was hard to distinguish, given the heterogeneity of house constructions observed as displayed in Figures 32 to 34. A possible reason could be that the distance to the villages on the Anarpurna Circuit Trek situated *below* 2 000 m as well as *above* 3 300 m of altitude is within reach by 2 days by foot (or a couple of hours by jeep nowadays) from Chame. Hence, influences from both lower and higher altitudes might have had an impact on the development of the architectural scene in Chame today. However the material selection for the hypothetical kitchens on which this research is based aim to reflect the construction materials present in the older house types observed, hence being referred to as the *vernacular* architecture of Chame as displayed in Figure 34a. This since it was considered more legit to investigate the impact on indoor thermal properties with respect to traditional building practices rather than modern buildings.

(a) Roof of wooden planks. (b) Roof of corrugated steel

Figure 31: Details of roof constructions in Chame

(a) Mud-brick bonded walls. (b) Wooden walls.

Figure 32: Different types of house constructions observed in Chame.

Openings

The size and prevalence of openings facing outside in the kitchens of Chame were differing between the different housing types. The fact that 24/25 households had at least one outer door to enter the kitchen is a direct result of - and in line with - the finding on that most kitchens were placed as a separate building of the residential unit. Nonetheless, simpler house constructions made by roughly cut, wooden planks did most commonly not have other openings than outer doors as displayed in Figure 33. In contrast, the house type referred to as the typical Chame house as well as the more modern houses made of wood with roofs of corrugated steel had large, glazed windows separated into different partitions by colored wooden beams as seen in Figure 34. These windows were found surprisingly big referring back to the suggested bioclimatic design strategies presented by Bodach, Lang, and Hamhaber (2014). Nonetheless, given that no reference is given to the meaning of *small* to *medium* sized openings in terms of exact dimensions, this evaluation is rather subjective. However, all partitions of glazed windows were not openable and only there for lighting purposes.

(a)

(b)

Figure 33: Dwelling units observed in Chame constructed by wood without windows.

(a) Type of house construction referred to as typical Chame house.

(b) Modern house construction of wood with large glazed windows.

Figure 34: Dwelling units observed in Chame with windows.

Due to the heterogeneity of housing types and openings observed, taking a position regarding the hypothesis on that general architectonic features provide limited prerequisites for the employment of natural ventilation hence becomes complex, in general as well as specifically for the kitchen environment. The evaluation of the ventilation efficiency resulting from the model applied with the opening configuration representing the current scenario is thus left to be discussed further below. Nonetheless, it is further worth to stress that the physical model representing the current scenario upon which this research is based does not represent a replica of an existing household in Chame, rather a hypothetical kitchen with features collected from statistical findings.

7.1.2 Household characteristics

The stove related household characteristics found in Chame suggest that the majority of the surveyed households are reliant on biomass fired cooking stoves to cover annual energy needs, a finding in line with what is presented as the general case in Nepal which further verifies the hypothesis on biomass dependence in remote high altitude regions. Moreover, the fact that firewood was found to be the most common type of solid biomass fuel reported to be used in Chame confirms the hypothesis made on firewood being the most commonly used type of fuel in cool temperate climates of Nepal.

(a) Piles of firewood along a road. (b) Storage of firewood on a courtyard.

Figure 35: Storage of firewood observed in Chame.

However, regarding the different stove types observed in Chame, it was found surprising that all households except from one (96 %) had access to some kind of ICS, falsifying the hypothesis on that the majority would be using a TCS. These findings deviate from surveys conducted in other districts in Nepal. A study of the Ilham region from 2016 presents that 51 % of the participating households only had access to a TCS (Dhimal et al. 2016). Additionally, in the inception study on energy efficient cooking technologies in seven high altitude districts situated above 2 000 meters of altitude performed by Nepal Energy Efficiency Programme (NEEP) (2011), the majority (53 %) of the population were using a TCS.

Hence, the results suggest which was later confirmed when talking to the community office on site that Chame is included in the ICS programme covered by the ACAP as a part of the governmental initiative of *Clean Cooking Solution for All* 2022. The fact that Chame is situated on the famous and well visited "Annapurna Circuit Trek" and thus covered by the objectives of the ACAP of sustainable tourism, livelihoods and energy might have promoted the development process towards clean cooking solutions. The recent completion of the motorable road is also a facilitating factor in the distribution of subsidized ICS in Chame. At a meeting with the responsible persons for the ICS development program at the office of AEPC in Kathmandu, it was further confirmed that the distribution of ICS to remote areas has been limited by the reduced access. Time, money and risk for physical breakage (as briefly mentioned in the background) was claimed to be hindering factors for ICS manufacturers in collaboration with AEPC to reach out to remote high altitude regions.

(a) (b)

Figure 36: Subsidized ICS not yet installed, found at the municipality office of the VDC of Chame, November 2017.

Nonetheless, it should once again be made clear that the majority of ICS observed in Chame were non-subsidized, rather locally customized or self made, of which the common denominator was the absence of a fire gate as well as the lack of heat transfer and/or combustion related improved features. Hence the design of the ICS differed significantly from the subsidized stoves presented in Figure 36. The question then evolves into why the ICS programme has not reached out to everyone in Chame, resulting in that households install provisional and mal-functioning ICS? Or were these installed before the ICS programme started, before the road was finished?

In a study comparing the effectiveness of ICS installed in the district of Mustang, a region adjacent to the north-western border of Manang, Reid, Smith, and Sherchand (1986) states that the people of Mustang were the first ones to import metal stoves due to the proximity to Tibet and being a part of the Tibet-India route. As a result, metal stoves have been present in Mustang ever since the mid 1900s, which potentially could have had an influence on the stove design in Manang, resulting in the more simple versions of ICS observed in Chame. Furthermore, the meeting at AEPC confirmed Chame to be an exception when it comes to the high prevalence non-subsidized ICS. The Tibetan stoves were suggested to (sometimes) be a more affordable and accessible alternative than the subsidized ICS due to the closeness to the Tibetan border.

Regarding the prevalence of different stove types, the fact that 22/25 (88 %) of the households had access to a gas stove out of which 10 households (40 %) exclusively used gas during summer, was found surprising. This suggests a rapid increase of households gaining access to gas stoves according to the latest National Population and Housing Census (NPHC) of the Manang district, where only 5/279 households were reported to mainly use a gas stove for cooking in 2011 (Central Bureau of Statistics 2014). The gas stove is claimed to be the most aspired cooking appliance after biomass being the natural first step up the energy ladder, as further confirmed by Kshirsagar and Kalamkar (2014).

Yet, interesting to note is that despite the access to a gas stove, this was not used to replace the ICS, resulting in the conclusion that households in Chame are reliant on solid biomass fuels to cover their annual energy needs. This further highlights the importance of making a difference between *access* and actual *usage* when assessing the current situation regarding stove related household characteristics. As presented in the results, the majority of the gas stoves were used for specific purposes such as "quick cooking" (e.g. boil water for tea), predominantly during warmer summer months. This indicates that cooking stoves *do* have multifaceted purposes in the domestic habitat such as heating. The seasonal stove usage profiles further validate the hypothesis on that the stove is used longer during winter for heating purposes. It hence becomes debatable if cleaner cooking technologies have the potential to substitute biomass fired cooking stoves if the need for other purposes such as heating are not reduced, being my first point in highlighting the importance of energy efficient building in high altitude regions. Nonetheless, the question of price might also be a reason to the modest use of gas despite having access to a gas stove, given that gas is more expensive than firewood.

7.1.3 Stove usage and ventilation practices

Stove usage and ventilation correlations
Based on the findings presented in the results, it is firmly confirmed that there is a consistent correlation between stove usage and the practice of opening openings both summer an winter. This since all households who used the stove employed natural ventilation during stove usage activity both summer and winter, and that the pattern of opening and closing openings coincided with the time of lighting as well as extinguishing the stove for the vast majority, if openings were not kept opened all day. The fact that one household closed openings *before* completion of stove usage activity during summer but not in winter appears to be rather contraindicative considering the stove as an internal heat source, hence is regarded as a potential error in the detailed documentation of the survey.

The same trend of a strong correlation between both stove usage and ventilation patterns was observed for the two larger groups of households investigated as well: the *general case* including both ICS and gas users (22/25) and *ICS users only* excluding households using gas (12/25). Hence, the consistency between all three groups of survey further validates the interconnection between stove usage and ventilation activities found for the exclusive number of households serving as a base for the calculations and simulations. This further justifies the extension of the duration of opened openings in the creation of ventilation profiles, ensuring to include the hours of stove usage activity. Here I realized the importance of putting the same value on field observations as mathematical methods when aiming to assess most common behavioral practices in the effort to describe reality.

Referring back to the hypotheses formulated in the beginning of this project, these results suggest that the employment of natural ventilation *does* have a strong correlation to the point in time of indoor burning of solid biomass fuels. Given the background on the wide-spread issue with elevated IAP levels in kitchens of biomass-reliant households, these findings indicate that letting fresh air flow through the building envelope is initiated by smoke accumulation generated by indoor combustion of solid biomass.

Consequently, it can be stated that the majority of the households under survey *do* take advantage of natural ventilation during stove usage activity, both summer and winter, somewhat falsifying the prediction on that openings generally would be kept closed even during stove usage in order to limit heat losses in winter. This becomes even more interesting given that the majority of the surveyed households used an ICS during winter, which ideally would reduce the smoke entering the indoor environment. Thus, the registered behavioral patterns imply that the residents must still feel a need to let in fresh air by opening openings despite the presence of a chimney, indicating that there is a potential problem with the design of the ICS present in Chame. These observations hence confirm what is presented in the background of the debatable success of the introduction of ICS worldwide as well as in the context of Nepal.

Stove usage practice

When it comes to the documentation on diurnal and seasonal stove usage habits, the recorded practice of using the stove was confirmed to be strongly correlated to the point in time when the main meals are taken, which in Chame was understood to take place twice a day both in summer and winter. These findings deviate from what Borgkvist (2016) found in when assessing stove usage patterns for 4 households in Ghorepani situated on 2 600 of altitude in the Myagdi district south west of Manang, on the southern border to Mustang. Here meals were cooked on a traditional stove three or four times a day, and stoves were sometimes lit throughout the night during winter. However, in Chame none of the households surveyed claimed to keep the stove on when sleeping, possibly due to the fact that only 6/25 households (24 %) used the kitchens as multi purpose rooms of which 3 households specified that they also slept in the kitchen. A limited number of households in Chame (4/25) had the stove lit the whole day during winter, justifying a divided stove usage profile for winter. These differences indicate that stove usage patterns deviate even between high altitude regions, which in turn suggest that different layouts and placement of kitchens in the dwelling unit as well as cultural differences might be reflected even in stove usage activity. It should however be noticed that the findings in Ghorepani are based on a smaller survey sample than the statistical assessment of behavioral practice made in Chame.

Nonetheless, summer stove usage practices documented and presented in this research correlates well to what is presented as general practice in typical households in the remote mountainous Humla province in Nepal. Here cooked meals are generally eaten twice a day (as further confirmed by Singh et al. (2012) to be the general case for mid and high hill regions) where breakfast is cooked between 07.00 - 09.00 and dinner around 18.00 - 21.00 (Fuller, Zahnd, and Thakuri 2009). Winter stove usage practice in Chame was however found to deviate from the general practice in Humla since the total number of hours of keeping the stove lit was recorded to be higher compared to summer.

As a result, the documented seasonal differences in stove usage activity confirm the hypothesis on that the stove is used more in winter for heating purposes in Chame. The general trend for all groups of households is suggested to be a prolonged stove usage activity particularly in the afternoon. However, the results presented for the group of households representing the base case display a substantial seasonal difference in stove usage also in the morning, with an earlier ignition as well as prolonged duration.

Ventilation practices
When it comes to ventilation practices, the fact that many of the surveyed households keep openings opened the whole day was found surprising, particularly that this occurred even in winter. The initial reflection was that this could have been an error in the questioning process, grounded in a potential misconception of the interpretation of the meaning of the term "ventilation". However, when analyzing the climate file regarding annual ambient temperatures in Chame, it became clear that high ambient temperatures do occur during the day in winter as well, in line with and explained by H. B. Rijal and Yoshida (2006) to be due to the low latitude and high insolation in mountainous regions of Nepal. The habit of keeping openings opened throughout the day in winter does hence not seem as unlikely. In addition, the fact that the perception of neutral temperatures have been documented to be significantly lower for people residing in high altitude settlements (H. B. Rijal and Yoshida 2006) (see section 2.4.4 in *Background*) can be a part of the explanation to the surprising winter ventilation patterns, given that the residents are accustomed to cope with harsh climatic conditions. However, as previously mentioned, the general practice and profiles assessed does not account for extreme weather conditions which most likely would influence the residents' behavior of keeping openings opened.

Nonetheless, a seasonal difference of the number of *"all day ventilators"* was found in the more detailed assessment of the correlation between stove usage and ventilation practices, suggesting that it is more common to have openings opened all day during summer than during winter (75 % and 40 % respectively). Furthermore, all respondents of the households representing the base case who employed all day ventilation also during winter had the stove lit during the same time, further emphasizing the interconnection between stove usage and ventilation activities as well as indicate a restrained employment of natural ventilation during colder periods. As a result, looking at the exclusive number of households representing the base case, these findings suggest that the practice of opening openings during winter is − without exception − restricted to the point in time of the day when an internal heat source is present.

A limited number of all day ventilators during winter was also found when assessing general ventilation practices for the two larger groups of survey, however with a less significant percentage difference (see Appendix A.2.4). Statistical comparisons of exact percentage differences between the three different groups of households are however ambiguous due to the fact that some households are included in all groups, of which the respective influence is more or less significant depending on the total number of households. Again, the intention with putting the results obtained for the base case in relation to the other groups of households are rather to validate general trends observed for the exclusive number of households representing the current scenario in the simulations and calculations.

When it comes to seasonal differences in opened area, it can nonetheless be stated that the results display a tendency among all groups of households to open a larger area in summer, of which the total area opened as well as seasonal difference was found larger when excluding households using gas. However, even if it was interesting to note that the average area opened is *larger* for the group of households only using solid biomass fuels than the households who occasionally use less-polluting gas stoves in summer are included, absolute comparisons between total area opened are more difficult to interpret since the households might not have the same opening prerequisites. It could be that the households only using ICS happen to have larger openings rather than opening more area due to a larger smoke accumulation. This would be very interesting to further investigate in order to assess to what extent the correlation between stove usage and opened area is dependent on stove types used. In doing so, an estimation of how the *functional* ventilation behavior of venting out biomass generated smoke is affected by switching to a cleaner gas stove could be obtained. Moreover, this would further answer the question if the current ventilation practices assessed for summer gas stove users are remnants from previous ventilation practices when using a biomass-fired stove, or if the practice of opening openings is limited when a cleaner stove is operated. However, this type of comparative assessment would require households with similar architectonic features in terms of prevalence and size of openings, hence falls outside the scope of this study.

To sum up, the fact that less number of households keep openings opened during the day in winter, and that the area opened was found (slightly) reduced compared to summer, indicate that the practice of opening openings varies over the seasons. The restrained ventilation patterns documented for winter further validates the hypothesis on that the employment of natural ventilation is restricted due to residential behavior during colder periods of the year.

As presented in the *Method* section, the difference in seasonal ventilation patterns are however only reflected in terms of point in time and duration of keeping openings opened in this research, since the same physical models − with the same opened area − were used for both summer and winter simulations. This due to the rather modest area difference found when adapting the opening sizes of the geometrical base case to the actual opened area (assessed by the seasonal profiles) when creating the physical model representing the current ventilation situation, referred to as the *base case*. Needed to be highlighted is that this was done for simplicity. In the scenario of that a seasonal difference of opened area were to be found prominent when applying the actual opened area to the base case, two different physical models would have been required for annual simulations of both airflow rates and operative temperature. The analysis of the climate files would then have had to be made accordingly, presenting seasonal rather than annual prevalence of temperatures, wind speeds and wind directions.

As a result, the simplifications made by discarding the seasonal area difference as "insignificant" is a clear example on trade-offs considering disparities between reality and the development of methods aiming to model reality. Consequently, it is important to bear in mind that a reduced opening area during winter would have resulted in higher indoor concentrations of CO, of which the magnitude is unknown and left for future research.

7.2 IAP assessment

7.2.1 Airflow rates

Impact of different opening configurations
The results obtained in this study confirm that naturally induced airflow rates can be increased significantly by only intervening in the building structures applying different opening designs. Increasing the opened area of single sided ventilation as well as employing cross ventilation were both shown to enhance ventilation efficiency. Nonetheless, taking advantage of cross ventilation by adding a window on the opposite facing wall was confirmed to generate the highest airflow rates, providing around 40 % higher air exchange rates than increasing single sided ventilation.

Comparison with previous studies
The air exchange rates presented for all cases under investigation are found in the higher end of or considerably higher than what previously has been reported in literature for typical village houses in developing countries. In the lack of empirical data, Zhang et al. (1999a) used estimated values of AER based on reported ranges of 2 h^{-1} – 24 h^{-1} in a similar IAP assessment. Furthermore, the AER resulting from the cases with single sided ventilation in this study fall within the same range as the highest average ventilation rates documented in the household ventilation classification formulated by Cowlin (2005) in the assessment of kitchen ventilation rates in Guatemala (21 h^{-1} – 50 h^{-1}). The AER resulting from the improved case with cross ventilation correspond to ventilation rates recorded for specific experiments in residential units of the highest ventilation classification (27 h^{-1} – 101 h^{-1}). However the range of air exchange rates obtained in this study fall within the same order of magnitude of AER as presented for kitchens in developing countries summarized and used by Johnson, Lam, et al. (2011) in the development of WHO guidelines on emission rate targets for household combustion technologies using a single zone model approach.

Validity of results
Airflow rates are dependent on both opening configuration and climatic conditions. Thus, commenting on the validity of the results presented in this study with respect to documentations on ventilation rates in other studies would be incorrect, given that site specific parameters for Chame were included in the airflow rate calculations.

7.2.2 Indoor concentrations of CO

General findings
The IAP assessment suggest that indoor concentrations of CO in high altitude settlements with similar architectonic features, stove usage and ventilation practices as assessed in this study risk to exceed health deteriorating limits, despite using an ICS fitted with chimney. This in accordance with previous IAP assessments of Nepalese kitchens where the relative reduction in CO levels by implementing an ICS with a chimney does not ensure a healthy indoor environment with respect to WHO IAQ guidelines (Singh et al. 2012; Parajuli, H. Lee, and K. Shrestha 2016). The magnitude of exceedance is shown to be a direct result of the fraction of pollutants entering the indoor environment from the combustion process (i.e. *fugitive* emissions) as well as AER. Both these parameters are further discussed below.

Role of fugitive emissions
The results present that there is a clear difference in indoor concentrations of CO between chimney reduction potentials of 30 %, 69 % and 90 %. This in line with what Reid, Smith, and Sherchand (1986) found when assessing the performance of chimney stoves depending on level of maintenance. When measuring indoor concentrations of CO before and after soot removal from a chimney, indoor CO levels decreased by a factor of 9. The crucial role of proper maintenance was further confirmed by Joseph, Sulpya, K. Dhakal, et al. (1985) during stationary CO measurements for simulated Nepali cooking conditions. Here it was proved that well-installed and maintained stoves with chimneys have the potential to reduce indoor levels of CO with a factor of 4 compared to non-maintained ICS. Moreover, if accounting for over-all fugitive emissions from chimney stoves, Reid, Smith, and Sherchand (1986) showed that adjusting ill fitting pots had the potential to decrease indoor concentrations of CO with a factor of 16 (Reid, Smith, and Sherchand 1986).

Consequently, this study reinforces the importance of understanding that distributing ICS does not have a cause-effect per sé. In correspondence with Dr. Alex Zahnd, the inventor of the *Smokeless Metal Stove* (SMS) successfully implemented in Nepalese high altitude settlements in Humla, the complexity with distributing ICS was firmly confirmed[3]. He claims that in order for an ICS programme to be successful, proper installation and training the residents on operation and maintenance procedures are essential.

[3]Dr. Alex Zahnd, International Project Director of the RIDS-Switzerland. E-mail communication, April 2018.

Role of passive ventilation

Coming back to the scope of this thesis, the results presented confirm the hypothesis on the significant role of passive ventilation strategies as a mean to improve IAQ in biomass-reliant kitchens in Nepal. In line with former predictions, peak concentrations of CO are displayed for the base case with the lowest ventilation rate. Enhancing naturally induced airflow rates by increasing the opened area of single sided ventilation as well as taking advantage of cross ventilation both show to have a substantial impact on IAP levels for all chimney reduction potentials, reducing indoor concentrations of CO with 39 % and 51 % respectively. Employing cross ventilation is hence declared to generate the highest ventilation efficiency with respect to the performance in reducing IAP levels among all cases of survey.

When it comes to reaching IAQ guidelines, indoor concentrations of CO fall below 1 hour guideline values for a chimney reduction potential of 69 % when cross ventilation is used. However for the cases with single sided ventilation, indoor concentrations of CO only reaches safe limits considering 1 hour guideline values with a chimney reduction potential of 90 %. Considering CO decay rates, the fact that indoor levels of CO reach safe limits within a couple of minutes for all opening configurations if keeping openings opened after the stove is extinguished, suggests that natural ventilation has a crucial role in ensuring a healthy indoor climate *after* stove usage as well.

Conclusively, parameters influencing the magnitude of fugitive emissions such as the improved features of the stove, material quality, proper usage and frequent maintenance of the chimney become crucial for the indoor air quality in kitchens with opening prerequisites only allowing for low ventilation rates. Worth to highlight in this study is however that passive ventilation becomes particularly critical in households with provisional or malfunctioning chimney stoves as observed in Chame and illustrated by Figure 37; an unexpected insight emphasizing the importance of architectural features allowing for sufficient natural ventilation during stove usage.

Figure 37: Stove generated smoke exiting a kitchen through an opened window and gaps between the walls and roof.

Resulting IAP levels

Referring to the more thorough analysis of the CO levels resulting from the chimney reduction potential of 69 % − selected to serve as a base for further analysis considering the representativeness of observations made in Chame − the fact that estimated CO levels for the base case exceed 1 hour guideline values with a factor 2 is worth to remark. Given that cooking activity was assessed to continue for several hours indicates that Nepali women and children risk to be exposed to elevated CO levels for longer than 1 hour at a time. This emerge as particularly problematic during winter time, when the stove is lit between 4 to 5 hours consecutively in the afternoon. As a result, indoor levels of CO exceeding guideline values with "only" 20 % − as presented to be the case for the kitchen with increased opened area − also becomes troublesome despite the initial reflection of a rather modest level of exceedance.

Significantly important is the fact that all households close openings when the stove is extinguished at night, suggesting that indoor levels of CO reached at steady state will prevail in the kitchen environment throughout the night, however gradually decreasing dependent on the rate of infiltration. Here it is vital to acknowledge that *no* opening configuration reach 8 hour guideline values for any chimney reduction potential (see Table 38, 39 and 40 in *Results*), even if increased ventilation efficiencies *do* reduce indoor levels of CO significantly. Considering the chimney reduction potential of 69 %, permissible indoor concentrations of CO for 8 hour exposure were exceeded by around a factor of 7, 4 and 3 for the base case, increase of opened area and cross ventilation respectively. As a result, the severity of IAP related health risks becomes dependent on both the level of air exchange rate as well as the total time spent in the kitchen after the stove is extinguished. More specifically, this develop into being especially perilous for households where the kitchen serves as a multi-purpose room, particularly for residents who also sleep in the kitchen.

Validation of results
Indoor levels of CO presented in Table 37 fall within the same order of magnitude as presented in similar IAP assessments of CO resulting from 1 hour operation of wood-fired cooking stoves reported in literature (Zhang et al. 1999a). For the case representing the current situation with the chimney reduction potential of 69 %, indoor levels of CO are congruent with the concentrations measured in mid-hill Nepalese kitchens during cooking activity on an ICS (67 mg/m^3 vs. 76 mg/m^3) (Reid, Smith, and Sherchand 1986). Furthermore, here the indoor levels of CO were assessed to be around 200 mg/m^3 less compared to cooking on traditional stoves without chimneys, in line with the findings of this study presented in Table 37. Moreover, the indoor concentrations obtained for the two improved cases correspond well to the CO concentrations measured at the approximated exposure height representing breathing level of a standing person of 1.5 m after cooking 1 hour on an ICS in an experimental setting conducted by J. Kandpal, Maheshwari, and T. Kandpal (1994).

However, consistent data from field measurements on resulting indoor concentrations of CO in Nepalese kitchens as well as general kitchens in the developing world is non-existent due to temporal and spatial variations in concentrations during the fuel burning cycle and different placements of monitors (Reid, Smith, and Sherchand 1986). Johnson, Lam, et al. (2011) further found that modeled CO concentrations were underestimated by 46 % compared to actual measurements, providing the explanation of that point measurements reflect the heterogeneous spatial distribution of CO rather than represent the overall concentration of the whole room. Exact comparisons between measured and simulated IAP levels are therefore hard and even unjustifiable to make. The legitimacy of comparing simulated IAP levels of different studies are also questionable, given the large variety of case specific input parameters having a significant impact on resulting indoor concentrations such as emission factors, kitchen volume and local climatic conditions.

As a result, the indoor concentrations of CO presented in this study serving as a base for the discussion above are not to be considered as *exact* or *absolute* values. Even if the assumptions and simplifications involved in the calculations and simulations are based on observations and data collected from a field survey, the resulting IAP levels are rather to be considered as *indicative* when it comes to the aim to assess the current situation. This due to the hypothetical nature of the research approach, of which one of the core aims is to investigate relative improvements. Hence, the CO concentrations presented are not valid for any specific household in Chame as already declared in the *Method* section. Indicative research is however still of value when it comes to bringing attention to societal phenomenons and raising awareness of potential risks. As an example, the fact that indoor concentrations of CO were shown to exceed IAQ guidelines for airflow rates considered as *high* implies that IAP levels risk to be worse in kitchens with even more limited possibilities to take advantage of passive ventilation.

Indicator pollutants and health aspects

Worth to further stress is that this IAP assessment is conducted with respect to CO only. CO is however *one* airborne compound of the cocktail of toxic substances and particles generated by combustion of solid biomass presented in section 2.1.1: *A global outlook*. Not only does high concentrations of CO imply high levels of $PM_{2.5}$ to which recurring exposure is regarded as the main reason to respiratory diseases associated with IAP. One can expect that indoor concentrations of other health hazardous substances also exceed permissible values for safe health, of which potential synergistic effects are not known. On that account, it is vital to acknowledge that the problematic issue of health deteriorating indoor environments resulting from indoor combustion of solid biomass does not end with evaluating concentrations of the indicator pollutant only.

Importance of stove design

Bringing back the subject of the performance of the ICS, the design of the improved features also have an impact on the IAP levels as presented in section 3.2.5: *Stove characteristics influencing IAP*. If the improved features do not address an increased combustion efficiency (CE), the generation of PICs risk to be worse than for traditional open fires. Anchored in Still et al. (2011)'s statement on that an increase of heat transfer efficiency (HTE) can result in two to three times more pollution per meal, the worst case scenario would be to operate an ICS designed only to improve HTE of which a large fraction of the generated smoke would enter the indoor environment. Hence, the observations in Chame become more alarming.

Since the majority of the households had a locally made ICS of provisional nature, several improved design features required to increase combustion efficiency such as a baffle, damper, a divided and leveled combustion chambers as well as a fire gate were often lacking. Not only does a provisional chimney-stove risk to stimulate the production of PICs due to the impeded possibility to regulate the exhaust flow in absence of a baffle and damper. A chimney being clogged by soot increase the risk of backflow as well as increases fugitive emissions from badly sealed joints and badly fitting pots. Consequently, an ICS lacking improved combustion features fitted with a malfunctioning chimney risk to aggravate the problematic issue of IAP for two reasons: a larger generation of PICs and a higher fraction of fugitive emissions entering the indoor environment.

Importance of user behavior

Important to note is that the design of the ICS provided by the government is developed to include improved features on both HTE and CE, and that research on optimized features is taking place at Kathmandu University. Nonetheless, households with subsidized stoves were observed to keep the fire gate opened during stove usage due to the habit of consecutive metering of the long wooden logs into the fire as displayed in Figure 38. Improper operation hence resulted in a significant smoke accumulation indoors. Moreover, since using moist fuel also result in higher emission rates of PICs during the combustion process, the fact that households were not drying the fuel risk to further exacerbate indoor air pollution levels.

Figure 38: Cooking activity on a provisional ICS observed in Chame.

Conclusively, this study has highlighted the fact that variations in stove design and improper operation of an ICS risk to result in elevated levels of IAP.

Future research
Still et al. (2011) found that increasing the opened area of a door is more efficient in reducing IAP levels than the combination of having an opened window and a hole in the roof. In this study it is however shown that adding a window to the opposite wall reduces indoor levels more than increasing the area of single sided ventilation. Assessing the ventilation efficiency for several different opening configurations in order to find an *optimized* passive ventilation configuration with respect to reducing IAP levels is hence intriguing to further investigate. Moreover, simulating IAP levels resulting from extreme weather conditions when openings most likely would be closed all day due to heavy rain, snowfall or strong winds would be interesting to assess. This in order to display a worst case scenario of which the resulting IAP levels could be put in relation to the results obtained for the cases when natural ventilation is employed.

7.3 Operative temperature assessment

Seasonal dependence and diurnal fluctuations
The results from the operative temperature assessment display that there is a wide distribution of indoor operative temperatures throughout the year for all opening configurations examined, indicating a strong seasonal dependence which in turn suggest that indoor operative temperatures are strongly influenced by the surrounding climate.

The poor thermal resistance of the building envelopes observed in field and applied in the the physical models was found to contribute to the seasonal dependence of indoor operative temperatures. T_{op} in all hypothetical kitchens were shown to follow the dynamics of ambient temperatures throughout the night both summer and winter when no internal heat source was present and openings were closed: T_{op} declines at the same rate as the ambient temperature gradually drops as displayed in Figure 29 and 30, indicating that neither the thermal mass nor the physical protection of the building envelope manage to preserve the heat generated by the stove after the stove is extinguished.

Nonetheless, the prominent peaks and declines in the more detailed assessment of the diurnal dynamics of T_{op} however confirm the hypotheses on that stove usage and ventilation *do* have a strong influence on the indoor thermal climate both summer and winter. Despite the clear increase of T_{op} during stove usage activity, the current ventilation patterns of keeping openings opened during the day result in that T_{op} even coincide with ambient temperatures after morning stove usage in winter for the airflow rates investigated as explained in the results. Consequently, the results suggest that the seasonal dependence of indoor operative temperatures presented in this study is both attributed to current ventilation patterns as well as the physical properties of the building envelope considering thermal capacity as well as level of infiltration of the house construction and building materials.

It is further worth to comment on the difference in influence of the surrounding climate between the opening configuration cases of investigation. The fact that the most drastic hourly variations in T_{op} for January 15th was shown for the case with cross ventilation was reconfirmed when analyzing the diurnal dynamics of T_{op} for other months of the year. This further verifies what Figure 29 illustrates, that the indoor thermal environment in kitchens with cross ventilation is subject to a higher level of influence by more rapid changes in local climate conditions.

Resulting indoor operative temperatures
When analyzing both annual frequency as well as diurnal fluctuations of indoor T_{op} resulting from the different opening configurations in more detail, the highest operative temperatures were shown to occur for the base case as expected due to the lowest airflow rates. Yet, the most common temperatures were initially found surprisingly high for all cases (between 18 ^{o}C to 20 ^{o}C for the base case and 16 ^{o}C to 18 ^{o}C for the improved cases) considering the high altitude and cold winters. However, given the high temperatures occurring during the summer months of June, July and August as well as the large diurnal temperature differences from March and onwards (see Figure 13 of monthly distributions of ambient temperatures), these temperatures earned reason.

Nonetheless, even if the most common indoor operative temperatures were found high and that the difference between the base case and improved cases in terms of most common temperature range consist of "only" 2 ^{o}C, it is important to look at the prevalence of temperatures in the lower end of the spectrum when investigating overall indoor thermal conditions. Only assessing most common temperatures does not display where the problem lies in this case. Rather, it is more interesting to evaluate the magnitude of thermal *dis*comfort by investigating the distribution and prevalence of lower temperatures.

Thermal discomfort
The results suggest that operative temperatures of 10 ^{o}C or below occur for a substantial part of the year for all opening configuration cases. More specifically, the accumulated percentages of total number of hours range from around 36 % to 42 % as presented in Table 41. Considering more extreme indoor operative temperatures falling below 0 ^{o}C, the accumulated percentages of the annual prevalence are comparatively more modest, ranging from 3.5 % to 6 % of the total number of hours of the year. Nonetheless, each and every hour of these three to five hundredsome hours below freezing equals one hour of enduring extreme cold climatic conditions indoors. As a result, this study confirms that Nepalese residents in high altitude settlements in the Himalayan region risk to live far below internationally recognized comfort standards.

Evaluation of different cases
Increasing naturally induced airflow rates is shown to result in a larger part of the year with indoor operative temperatures below 10 ^{o}C and 0 ^{o}C as presented in Table 41. It is however worth to notice that the annual prevalence of operative temperatures between the two improved cases was not found strikingly different, neither for T_{op} below 10 ^{o}C nor below 0 ^{o}C. A part of the explanation is what previously has been mentioned regarding the current ventilation pattern of keeping

openings opened between morning and afternoon stove usage, resulting in that T_{op} coincide with ambient temperatures regardless opening configuration. As a result, operative temperatures for all opening configuration were found to be the same during a couple of hours during the day. A further analysis confirms that this occurs for the majority of the months of the year for the two improved cases, partly explaining the modest difference in the present quantification of thermal discomfort. However when looking at the diurnal dynamics of T_{op} for January 15th, indoor operative temperatures are displayed to be similar for both improved cases, presenting a scenario when the employment of cross ventilation does not necessarily equal a substantial decrease in T_{op} during winter stove usage. The question remains if this is only attributed to low wind speeds and other characteristics of the surrounding climate contributing to momentary reduced ventilation rates? Or can it be that cross ventilation provides a more efficient air exchange with a limited cooling effect? This analyze falls outside the scope of this study and is hence left for future research.

Worth to further remark is that even if the prevalence of hours falling below 0 ^oC in winter were found less for the base case, the relative difference compared to the two improved cases were found rather moderate. This indicates what Figure 29 of January 15th exemplifies: Despite the fact that the highest temperatures during stove usage are reached for the base case with the lowest ventilation rates, this does not prevent T_{op} to stay below 0 ^oC with the current ventilation patterns and when the initial indoor thermal conditions are below a certain limit. As a result, this further suggests that the range of airflow rates investigated in this study does not differ in the performance of maintaining indoor operative temperatures above 0 ^oC during colder periods of the year, given the current architectonic features and behavioral practices.

Improving thermal comfort

Previous studies have shown that enhancing the thermal resistance of building envelopes in Nepalese settlements has the potential to improve indoor thermal comfort. As found in Borgkvist (2016)'s study of thermal comfort of vernacular houses in Ghorepani, a project also conducted parallel to the CIMCEB collaboration in Nepal, adding insulation to the roof and outer walls as well as improving thermal bridges have the potential to increase the mean operative temperature with 5 ^oC during the coldest winter days. Fuller, Zahnd, and Thakuri (2009) further suggest that reducing unwanted infiltration is an efficient way of improving thermal comfort in Nepalese high altitude dwellings. Additionally, building structures with a high thermal mass would better store the available energy from the stove and incoming solar radiation, in turn allowing for a gradual release of the stored heat throughout the night and thereby make the indoor environment more resilient to dynamic fluctuations of ambient temperatures. On that account it is presumed that there are energy efficient building techniques applicable to the context of Chame having the potential to improve thermal comfort in settlements with similar building characteristics as simulated in this study. Nonetheless, given that the documented ventilation patterns provide air exchange rates of a magnitude resulting in that indoor operative temperatures coincide with ambient temperatures during the day, *both* physical parameters of the house construction as well as efficient ventilation strategies would be required to prevent indoor operative temperatures to drop below 0 ^{o}C during winter.

Validity of results: simulation tool and extreme values

Even if the results suggest that the indoor thermal climate fall below international comfort standards for a substantial part of the year for all cases of investigation, extremely high temperatures were observed to occur sporadically during summer. As explained in the results, this is partly due to the synergistic effect of stove usage activity and high insolation during that time of the day resulting from the rather static simulation procedure not considering change in user behavior. In reality, an exceptionally warm summer day is expected to result in a somewhat limited stove usage activity as well as extended ventilation patterns to increase the airflow through the kitchen. Reversibly, extreme cold conditions, heavy precipitation or strong winds would probably result in a restricted employment of natural ventilation and extended stove usage. Consequently, these deviations visualize the drawbacks with generalizing human behavior in a dynamic context determined by natural forces, however required in the effort to examine or assess general trends.

Moreover, due to the fact that the stove size (in terms of generated heat) was shown to be influential in both airflow rate simulations as well as in the operative temperature assessment, it is important to once again note is that the resulting operative temperatures and diurnal fluctuations presented are valid for an internal heat source of 4 000 W. Hence, this is vital to acknowledge when evaluating the indoor thermal climate with respect to the the ability of the present internal heat source to heat up the indoor environment during winter.

In addition, it is further worth to highlight that the more detailed evaluation of the diurnal dynamics of operative temperatures are based on *one*, randomly chosen day for each season. Hence, the temperature differences between operative temperatures and ambient temperatures presented are not to be considered as representative for all January or July, nonetheless the whole winter or summer. This would require an investigation of temperature differences for all days of each month, which is left for future research. The diurnal assessment presented rather serve as an *example* of hourly fluctuations of T_{op} over the day.

Future research
Given that the magnitude of leakage was shown to have a noticeable influence on resulting AER, it would be interesting to assess to which magnitude improperly sealed building envelopes affect the operative temperature by conducting a sensitivity analysis only focused on infiltration. This in order to further investigate where it would be most beneficial to intervene regarding enhancing the airtightness versus the thermal resistance of the building envelope.

Moreover, investigating how much energy that would be required to *maintain* a certain indoor operative temperature (e.g. 18 ^{o}C) in the physical models representing Nepalese settlements would further be interesting to assess. These types of simulations can be performed in DEROB, but is left for future research due to limited time. Figure 39 and 40 display some examples of indoor kitchen environments surveyed in Chame.

Figure 39: Indoor environment of a kitchen in Chame.

(a) (b)

Figure 40: Indoor environments of two kitchens in Chame.

7.4 Synthesis of results

The following section provides a synthesis and evaluation of the correlation between passive ventilation, resulting IAP levels and the impact on the indoor thermal comfort, of which a holistic outlook follows where aspects of sustainability is applied to the linkage between energy poverty, energy efficient building, ventilation efficiency and public health.

7.4.1 Passive ventilation, IAP and thermal comfort

Conflict between indoor air quality and thermal comfort
Combining the results obtained from the four different research steps discussed above, this study confirms that there is a conflict between ensuring a healthy indoor air quality by taking advantage of passive ventilation and maintaining an acceptable indoor thermal comfort in biomass reliant households of high altitudes. As explicitly quantified in this research, employing cross ventilation − providing the ventilation efficiency required to respect 1 hour IAQ guidelines for the widest range of fugitive emissions − is balanced against a 6 % higher annual frequency of hours with operative temperatures falling below 10 ^{o}C compared to the base case.

The findings from the interview study further suggest that residents in Chame prioritize to limit ventilation associated heat losses over reducing stove-generated smoke accumulation at night. Despite the fact that CO decay rates for neither opening configuration require the openings to be opened for more than a couple of minutes to meet IAQ guidelines for safe health, it is however unknown to which magnitude these minutes would affect indoor operative temperatures given that a high CO decay rate is a direct result from a high AER. This investigation is however outside of the scope of this study and left for future research.

Role of opening configuration
Opening configurations allowing for ventilation rates sufficient to meet 8 hour IAQ guideline values already during stove usage would eliminate the need to keep openings opened after the stove is extinguished both morning and evening. Associated heat losses would thereby be avoided, suggesting that further increasing ventilation efficiencies when the stove is lit is desirable when it comes to preserving the stove-generated heat in kitchens where passive ventilation is proven to be vital in reducing accumulation of IAP. However, the fact that a higher airflow during stove usage would decrease indoor operative temperatures needs to be considered when evaluating the over-all thermal benefits with further increased ventilation rates. Here it becomes interesting to question if the relative impact on

indoor operative temperatures is *less* for high ventilation rates during stove usage (ensuring IAP levels below 8 hour IAQ guidelines), than for lower ventilation efficiencies (only meeting 1 hour IAQ guidelines) which thereby require a short time of continued ventilation after the stove is extinguished? Yet, it is unclear until which magnitude airflow rates are realistic considering other inconveniences resulting from augmented airflows through the building envelope.

Given the inverse correlation between naturally induced airflow rates and thermal comfort, developing a method to find opening configurations providing a well-balanced ventilation efficiency with respect to both indoor air quality and thermal comfort would be of great significance in order to evaluate the case specific feasibility of adopting passive ventilation as a mean to mitigate exposure to indoor air pollution. This however requires the complex definition of what an "acceptable trade-off" would be and falls outside the scope of this study, considered as a next step in further investigating the correlation between ventilation efficiency and thermal comfort.

Role of energy efficient building
To further elaborate on the association between architecture, ventilation efficiency and thermal comfort: Considering the harsh indoor climate in winter presented in this study, could improving thermal comfort by applying energy efficient building techniques somehow improve the prerequisites for employing natural ventilation and thereby reduce indoor levels of IAP? Given the non-existent access to clean heating sources in rural and remote areas of Nepal, building envelopes taking better advantage of the available energy and thereby providing a warmer and stable indoor climate are predicted to encourage residents to take advantage of natural ventilation when needed, limiting the trade-off between keeping warm at present versus long term health impacts.

Role of behavioral practices
When it comes to residents' habits of opening openings and thermal comfort, a more restricted ventilation pattern between morning and afternoon stove usage activity would limit the risk of indoor operative temperatures to coincide with ambient temperatures. A higher initial indoor temperature at the time of lighting the stove in the afternoon would further result in higher indoor temperatures during stove usage. In turn, this would allow openings to be kept opened longer after the stove is extinguished at night before indoor operative temperatures fall below extreme values. Further investigation of the impact of altered ventilation practices on ventilation efficiency and thermal comfort is however left for future research.

Complexity with climate responsive architecture
Given that the climate analysis of Chame showed that ambient temperatures can rise significantly during the day even for colder parts of the year, the practice of keeping openings opened between morning and afternoon stove usage might however be beneficial for days when ambient temperatures rise faster than what indoor operative temperatures do. This illustrates the complexity with appropriate bioclimatic design strategies for house constructions in geographical regions with extreme diurnal temperature fluctuations. Consequently, accounting for *seasonal* as well as *diurnal* dynamics of ambient temperatures is vital in the architectural design of a high altitude settlement adapted to both warmer and colder periods of the year (e.g. when dimensioning the thermal mass of the building structure) to comply with the concept of energy efficient building.

7.4.2 Infiltration, IAP and thermal comfort

A further remark to be made in the discussion of the correlation between building characteristics, IAP and thermal comfort is the impact of the airtightness of the building envelope on the resulting concentrations of CO. As suggested above, reducing unwanted infiltration is an efficient way of improving the thermal comfort in high altitude Nepalese dwellings (Fuller, Zahnd, and Thakuri 2009). The fact that the leakage parameter of 10 $l/s/m^2$ applied in the simulations is considered as high further indicates that there are significant improvements to be made in Nepalese houses regarding unwanted infiltration. As Blower Door Tests were not performed in Chame, evaluating whether the houses observed in field are well adapted to the surrounding climate considering the climate responsive design techniques suggested by Bodach, Lang, and Hamhaber (2014) is however not possible when it comes to airtightness.

Worth to acknowledge is however that despite a high leakage parameter employed in the simulations, the resulting concentration of CO *still* exceed IAQ guidelines for safe health stated by WHO and the Nepalese government. As a result, in the scenario of a *too* high leakage parameter than what is representative of houses in Chame, indoor concentration of CO risk to be even higher than what this study presents. This is important to acknowledge in the evaluation of resulting IAP levels, given that the leakage parameter was shown influential in the airflow rate assessment. An interesting question for future research hence becomes: To what extent does unintentional natural ventilation in form of infiltration improve the IAQ in Nepalese kitchens?

Considering the simulations performed in this study, the influence of leakage was shown to differ between the different opening configurations. The relative contribution to the total natural ventilation rates was found to be dependent on wind speed and wind direction, however overruled by the magnitude of airflows resulting from opening windows and doors. As a result, to thoroughly investigate the overall impact of leakage on IAP levels when openings are *closed*, simulation tools including dynamic combustion models *and* climate specific data in which physical models with different leakage parameters can be integrated would be required. However, as far as the author is concerned, there are no such softwares up to date. Computational fluid dynamics (CFD) have the potential to simulate transient IAP levels however does not account for dynamic climatic conditions. Consequently, laboratory tests or actual field measurements in kitchens with varying levels of effective leakage area is presumed to be most suitable in order to assess the exclusive impact of infiltration on IAP levels resulting from indoor burning of solid biomass.

7.4.3 Conflict between bioclimatic design and IAQ

Given the results provided in this study and following discussions above, it is confirmed that there is a conflict between suggested bioclimatic design strategies and IAQ in biomass-reliant Nepalese high altitude settlements. As presented by Bodach, Lang, and Hamhaber (2014), climate responsive building designs aiming to limit heat losses suggest openings to be small to medium sized which risk to compromise required ventilation efficiencies. Furthermore, a compact building layout and solid, airtight walls are suggested to enhance indoor thermal comfort which however risk to result in elevated concentrations of IAP during combustion of solid biomass. Hence as displayed in this study, IAP levels risk to exceed IAQ guidelines for safe health if the area and relative placement of openings facing outside do not allow for sufficient natural ventilation rates.

7.4.4 What about other rural settlements at higher altitudes?

Indoor concentrations of CO presented for the case of *"No chimney"* indicate that the indoor air quality would be significantly worse in kitchens with open fires or TCS where all biomass related pollutants enter the indoor environment. Despite the optimistic governmental target of *Clean Cooking Solutions for All* by 2022, AEPC confirmed at a meeting in Kathmandu, November 2017, that the observations made in Chame where 24/25 households had access to some kind of metallic stove with chimney was an exception compared to the situation in the rest of rural Nepal. ICS distribution programmes executed by the AEPC comprise a total number of 3 million subsidized ICS, of which 1.4 million was ordered and manufactured however not necessarily distributed or in use up to date. Here it was confirmed that there is a persistent problem with manufacturers who are reluctant to distribute stoves to remote areas in Nepal, especially in the far west, due to the costly and inconvenient transportation.

Nonetheless, 83 % of the total Nepalese population of 26.5 million reside in rural areas characterized by an extensive dependence of solid biomass fuels. So what about other rural settlements in Nepal, which are not eligible for or reached by the subsidized stoves? For how long will they continue to use solid biomass in open fires or unclean stoves and thereby risk to be exposed to accumulated health deteriorating levels of indoor air pollution? Considering the predicted continuation of the wide spread energy poverty and correlated dependence on solid biomass fuels the coming decades − this is where taking advantage of natural ventilation becomes vital.

Yet, people residing on even higher altitudes than Chame where the climate is more harsh, ventilation possibilities and the practice of opening openings risk to be further restricted. In these topographical regions, dung is used as fuel since there is no or limited access to firewood (H. B. Rijal and Yoshida 2006). Dung has further been reported to be even more polluting due to a higher emission factor during combustion (Zhang et al. 1999b; J. Kandpal, Maheshwari, and T. Kandpal 1994). As a result, it is presumed that the higher you climb in Nepal, the more pertinent becomes the trade-off between exposure to IAP and thermal comfort.

7.4.5 Aspects of sustainability

Energy provision and energy poverty
There are two main aspects on energy provision within the concept of sustainable development. Firstly, access to energy should satisfy basic human needs, improve social welfare as well as facilitate economic development. Secondly, production and provision of energy should not compromise the quality of life for current and future generations or the carrying capacity of our ecosystems (Goldemberg 2000).

Being reliant on solid biomass fuels to cover daily energy needs can hence be stated to fail in both criteria presented above. If combusted indoors without sufficient ventilation, this study has shown that IAP levels risk to exceed IAQ guidelines for safe health. Associated health impacts both hinder economic development and compromise life quality (World Health Organization 2000; Rehfuess 2006), hence are of great socio-economic importance. In addition, extensive use of fire wood for heating purposes accelerates the ongoing deforestation which have severe impacts on natural habitats of which humans are dependent (Natural Trust for Nature Conservation 2018b). As a result, for countries like Nepal where current societal structures and function of the society are based on an unsustainable domestic energy supply, striving towards eradicating energy poverty becomes a question of public and environmental health which in turn lay the foundation for a sustainable economic and societal development.

It is further widely adopted that economic growth is required for switching to cleaner fuels (Surendra et al. 2011; Malla 2013). The health burden caused by exposure to IAP however prevents the economic development required in order to step up in the energy ladder as suggested by World Health Organization (2000). A *catch-22* scenario is thus a fact in societies where a continued use of solid biomass is predicted. Hence, where to start?

Sustainable interventions
The research questions of this thesis address similar concerns as being raised in the guidelines provided by WHO on household fuel combustion (World Health Organization 2015). The scoping questions in line with what is examined here involves:

1. How clean is clean enough?

2. What can be made in the transition period of fully adopting cleaner cooking technologies?

There are different strategies in how to approach the problematic issue of IAP in the kitchens of the developing world reliant on solid biomass fuels. Given the results presented in this study it can be declared that both intervening at the source of pollution as well as in the living environment is essential for reducing IAP levels below safe limits. Access to cleaner fuels is however as previously stated a matter of poverty level hence a result of economic situation, both on an individual and national scale. This study however suggest that having access to a cleaner gas stove does not necessarily mean giving up the biomass fired cooking stove, a fact becoming interesting in the discussion of successful interventions. Is the limited use of gas a question of cost, since gas is much more expensive than fuel wood? Or only due to that gas stoves lack the additional values that biomass fired cooking stoves provide of which heating is essential in high altitude regions? What can then be done in the transition period before the energy poverty in Nepal is eradicated and all households have access to cleaner cooking *and* heating technologies?

Intervening at the source of pollution

A first step in the governmental initiative of *Clean Cooking Solution for All 2022* has been focused on distributing ICS. However, as shown in this study and confirmed by previous research and observations, installing an ICS does not have a cause effect per sé. Given the observations made in Chame on smoke accumulation in kitchens despite the presence of an ICS fitted with chimney, the first question of *"How clean is clean enough?"* became the driving force to throughly go to the bottom with the parameters influencing the debatable success of the ICS. The results of this thesis reinforce the fact that the severity of IAP levels depends on the magnitude of emissions entering the indoor environment, resulting in the concern that even if a chimney stove reduce pollutant concentrations significantly, IAP levels still risk to exceed guideline values for safe health.

Thus, do the residents in Chame live in the dishonest belief that the mere presence of a chimney ensure smoke levels below safe limits, or have they just accepted the fact that the level of smoke reduction is "as good as it gets" compared to a TCS? Cooking over open fire or on a TCS is the natural reference scenario for the residents when evaluating the ICS, hence is presumed to affect the perception of a stove's performance in reducing indoor smoke accumulation.

Despite required efforts and resources allocated on training in usage and maintenance, the success and correlated sustainability of an ICS programme is highly dependent on socio-cultural acceptance (Kshirsagar and Kalamkar 2014). In some cultural contexts in Nepal, the ICS risk to compromise the additional cultural values provided by traditional stoves or open fires such as smoking food, drying and preserving thatched roofs as well as being a social gathering place. Rejection of ICS has been claimed to occur if these factors are valued higher than the noticed benefits of the ICS (Kshirsagar and Kalamkar 2014). Additionally, Hanna, Duflo, and Greenstone (2016) found that the usage of ICS declined as the required maintenance and proper operational measures were neglected. Residents hence began to use their TCS simultaneously, a phenomenon claimed to stress the significance of including human behavior in the theoretical feasibility of employing new technologies.

Intervening in the living environment
For the reasons discussed above in combination with the results presented in this study, intervening at the living environment by ensuring for sufficient ventilation possibilities in house constructions is declared as an essential component in order to meet IAQ guidelines for safe health in biomass dependent households. It has been shown that increasing the ventilation efficiency can be achieved by only intervening in the physical structure of the building envelope by applying alternative opening configurations (hence no modification of ventilation patterns), stressing the importance of architectural prerequisites allowing for required airflow rates.

Nonetheless, the feasibility of introducing larger and/or alternative placements of apertures in the kitchen envelope is determined by the priority of the residents − a smoky versus a cold indoor environment − if not energy efficient building structures including passive heating technologies are applied and energy poverty is eradicated simultaneously. Yet, modernizing vernacular architecture without loosing cultural values risk to be a potential conflict due to the central role of culture and religion in the spatial planning and architectonic expression of the Nepalese dwelling unit (Toffin 1991). Cultural aspects are thereby essential to thoroughly consider in intervention strategies targeting the physical features of the house construction in order to be accepted.

Consequently, having a holistic view on IAP-reducing interventions including the residents' perception of the problem is essential in order to obtain long term, sustainable solutions on preventing health impacts correlated to *both* stove generated indoor air pollutants as well as cold indoor environments.

8 Conclusion

In the following sections, the conclusions of this thesis will be presented. Explicit answers of the research questions will first be provided, summarized from the findings presented in the results and correlated discussion, followed by an overall conclusion and personal reflections including a final outlook on the association between energy, architecture, health and environment within the concept of energy efficient building and sustainable societal development.

8.1 Research questions

- **Identify** and **investigate** stove usage and ventilation patterns in high altitude settlements of Nepal

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Identifying stove usage and ventilation patterns
After the field study of the high altitude settlement of Chame, Manang, it is confirmed that stove usage activity mainly take place twice a day, of which a seasonal difference was found and distinguished by an extended duration of stove usage during the colder parts of the year (see Figure 20 and 21). The majority of the surveyed households were using solid biomass to cover their energy needs where firewood was the most common fuel type used, as presented in Table 28 and 29 as well as in Figure 17 and 18. Most of the households were also taking advantage of natural ventilation during stove usage, and common practice was to keep openings opened also during the day, summer as well as winter (see Figure 22 and 23). The ventilation patterns were however found to be somewhat restricted during colder parts of the year, both in terms of total time opened per day as well as in opened area. However, the difference in opened area between summer and winter was found surprisingly modest. As a result, the seasonal variation in ventilation practice is declared to be mostly attributed to the point in time and total duration of keeping openings opened.

Correlation between stove usage and ventilation patterns
A consistent correlation was found between stove usage and ventilation patterns both summer and winter in households reliant on solid biomass fuels to cover their energy needs (see Table 31 − 34). The fact that the practice of opening openings was coinciding with the point in time of stove usage activity, in combination with the observations made on malfunctioning chimney stoves, the results of this study imply that the employment of natural ventilation is initiated by stove related indoor smoke accumulation. However, adequately substantiated conclusions on whether the ventilation practice is altered for residents using cleaner gas stoves fall beyond the scope of this study.

- **Assess** the ventilation efficiency of the current ventilation situation considering the accumulation of IAP generated by indoor burning of solid biomass fuels with respect to international and Nepalese standards on indoor air quality

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The results suggest that the airflow rates generated by the architectonic features, stove usage and ventilation practices documented in Chame risk to be deficient in ensuring a healthy indoor air quality during operation of a biomass fired cooking stove. This despite the presence of an ICS fitted with chimney, and that the vast majority take advantage of passive ventilation during stove usage activity.

1 hour IAQ guidelines
Indoor concentrations of CO were confirmed to be a direct result of air exchange rates as well as the fraction of stove generated emissions entering the indoor environment as presented in Table 37. When accounting for a range of hypothetical pollution reduction potentials provided by a chimney, averaged indoor concentrations of CO during 1 hour of stove usage exceed 1 hour IAQ guidelines presented by WHO with a factor of 4.4 and 1.9 for a reduction of indoor emission rates of 30 % and 69 % respectively. Only a chimney reduction potential of 90 % ensure IAP levels below safe limits with respect to 1 hour exposure (see Table 38).

Compared to the Nepalese IAQ standard, the corresponding factors of exceedance are reduced to 3.8 and 1.7 for the reduction potentials of 30 % and 69 %, given the higher limit values in this standard. Similarly, as for the comparison with WHO guidelines, only a chimney reduction potential of 90 % reduce CO levels below safe health limits with the current opening configuration, stove usage and ventilation practice (see Table 38).

8 hour IAQ guidelines

Permissible indoor concentrations for 8 hour exposure stated in the WHO and Nepalese IAQ standards were shown to be exceeded regardless of chimney reduction potential. More specifically, indoor levels of CO exceeded safe limits with a factor of 15.3, 6.7 and 2.2 for the chimney reduction potentials of 30 %, 69 % and 90 % respectively (see Table 38).

Assessment of current situation: Chimney reduction potential of 69 %

In November 2017, the majority of the ICS observed in Chame were of provisional nature lacking improved combustion features fitted with malfunctioning chimneys. Moreover, even if there was a fire gate, this was kept open by the long wooden logs gradually metered into the fire. Additionally, no practice of drying the fuel before use was documented. Under the pretext that a chimney reduction potential of 69 % correspond to the IAP levels experienced in the kitchens of Chame, indoor concentrations of CO representing the *current situation* are estimated to exceed 1 hour and 8 hour WHO IAQ guideline values for safe health with an approximate factor of 2 and 7 respectively (see Table 38).

Furthermore, high indoor concentrations of CO indicate that levels of $PM_{2.5}$ and other toxic substances resulting from combustion of solid biomass are likely to be elevated as well. Given that cooking activity was documented to continue for several hours (Figure 20) and that openings were closed when the stove was extinguished at night (Table 31 − 34), the residents are exposed to elevated IAP levels for longer than 1 hour at a time. As a result, the severity of the situation becomes dependent on the total time spent in the kitchen *during* as well as *after* stove usage activity. This is especially problematic in households where the kitchen serve as a multi-purpose room, particularly for residents sleeping in the kitchen.

Comments on current ventilation situation

Provisional chimney stoves with low combustion efficiency and malfunctioning chimneys in combination with improper stove operation risk to aggravate the problematic issue of IAP by a larger generation of PICs and higher fractions of fugitive emissions entering the indoor environment. Taking advantage of natural ventilation hence becomes crucial, reinforcing the importance of well planned opening designs in the building envelope allowing for sufficient passive ventilation rates ensuring for a healthy indoor air quality.

- **Examine** the efficiency of alternative passive ventilation strategies considering the ability to reduce the accumulation of IAP to not exceed international and Nepalese guideline values for indoor air quality

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This study confirms that increasing natural ventilation by only intervening in the building structure applying different opening configurations has the potential to reduce indoor concentrations of CO significantly. Increasing the opened area of single sided ventilation with around 100 % is shown to increase airflow rates with 60 %, resulting in a reduction of CO levels with 39 % during stove usage activity. Employing cross ventilation by adding a window of the same size to an opposite facing wall however result in a higher increase of airflow rates of 100 % compared to the base case, reducing CO concentrations with 51 % (see Table 36 and 37).

Respecting IAQ guidelines
Despite the substantial reduction of indoor CO levels presented for both improved cases, only cross ventilation showed to reduce CO levels below safe limits with respect to 1 hour IAQ guidelines for the chimney reduction potential of 69 % as displayed in Figure 37. More specifically, an increased opened area of single sided ventilation result in CO concentrations exceeding WHO 1 hour IAQ guidelines with a factor of 2.7, 1.2, 0.39 for emission reduction potentials of 30 %, 69 % and 90 % respectively. Compared to the Nepalese IAQ standard, the corresponding factors are reduced to 2.4, 1.04 and 0.34. Thus, increasing the opened area of single sided ventilation only respect limit values for 1 hour exposure if 90 % of the stove generated pollutants are vented by the chimney (see Table 39).

Cross ventilation is however shown to reduce CO levels below safe limits with respect to 1 hour IAQ guideline values for both chimney reduction potentials of 69 % and 90 %, corresponding to 0.94 and 0.31 of the permissible values respectively. Only the worst case scenario of the highest level of fugitive emission represented by a chimney reduction potential of 30 % result in exceeding 1 hour WHO guidelines with a factor 2.1. The equivalent factors for the Nepalese IAQ standard are further reduced to 1.9, 0.82 and 0.27 for the chimney reduction potentials of 30 %, 69 % and 90 % respectively (see Table 40).

Conclusively, taking advantage of cross ventilation is confirmed to be a more efficient alternative than increasing the opened area of single sided ventilation when it comes to reducing IAP levels with passive ventilation strategies in the climatic context of Chame.

Nonetheless, using cross ventilation does not ensure a healthy indoor environment with striking marginals considering 1 hour IAQ guidelines. Additionally, neither of the improved cases examined ensure a safe indoor air quality with respect to WHO and Nepalese 8 hour guidelines for any chimney reduction potential. Considering the chimney reduction potential of 69 %, an increased area of singled sided ventilation and the employment of cross ventilation exceed safe limits for 8 hour exposure with 4.1 and 3.3 times respectively (see Table 39 and 40). It is thereby reconfirmed that the severity of the elevated IAP levels presented in this study becomes dependent on the total time of exposure. As a result, to completely eliminate the health risks associated with indoor burning of solid biomass, opening configurations allowing for higher ventilation rates during stove usage are required.

- **Evaluate** the current ventilation situation as well as alternative passive ventilation strategies considering the performance in reducing IAP levels and the resulting impact of ventilation efficiency on indoor thermal comfort

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Ventilation efficiency and thermal comfort
The expected inverse correlation between ventilation efficiency and thermal comfort was confirmed and quantified. This is reflected both in annual prevalence of specific temperatures (Figure 28) as well as in the diurnal dynamics of operative temperature in kitchens with different opening configurations (Figure 29 and 30). The most common temperatures occurring on an annual basis fall within the range of 18 ^{o}C to 20 ^{o}C for the base case with the lowest ventilation rate, whereas the most common temperatures for the two improved cases were shown to be between 16 ^{o}C to 18 ^{o}C.

This study however highlights the importance of comparing the magnitude of thermal *dis*comfort when evaluating the impact of different opening configurations on resulting thermal comfort, given the high prevalence of hours with lower operative temperatures. Annual frequencies of temperatures below 10 ^{o}C were shown to be higher for opening configurations allowing for larger airflow rates during the same opening time, corresponding to 35.7 %, 40.7 % and 41.6 % of the total number of hours in a year for the base case, increase of opened area and cross ventilation respectively (see Table 41). Considering the more extreme temperatures below 0 ^{o}C, the annual hourly prevalence was found more modest amounting to 3.5 %, 5.8 % and 6.0 % of the hours in a year for the same consecutive order of opening configuration cases investigated (see Table 42).

Influence of behavioral practice and building characteristics on thermal comfort
The documented ventilation pattern of keeping openings opened between morning and afternoon stove usage result in that indoor operative temperatures coincide with ambient temperatures for a couple of hours during the day, as exemplified by Figure 29. This can partly explain that T_{op} fall below 10 ^{o}C for a substantial part of the year for for all opening configuration cases, and below 0 ^{o}C in colder winter months. The poor thermal resistance of the building envelope was further shown to contribute to the cold indoor environment since operative temperatures were decreasing with the same rate as ambient temperatures after the stove was extinguished at night (see Figure 29). As a result, the difference in annual prevalence of hours below 10 ^{o}C and 0 ^{o}C between the opening configuration cases of investigation is thus mostly attributed to the influence on T_{op} resulting from different airflow rates through the kitchen during stove usage activity. This is convenient in the combined evaluation of an opening configuration's performance in reducing IAP levels as well as the respective impact on indoor thermal climate since the IAP assessment in this study is conducted with respect to the period of time when the stove is lit.

Evaluation of the different opening configuration cases
None of the opening configurations investigated provide an indoor thermal climate of which temperatures are maintained above 0 ^{o}C during colder periods of the year. This further implies that the reduced airflow rate provided by the base case has a limited significance in terms of maintaining indoor operative temperatures above freezing when indoor thermal conditions are below a certain limit. The results further suggest that the significantly larger ventilation efficiency provided by cross ventilation during winter stove usage does not equal a substantial decrease in T_{op} put in relation to the impact resulting from increasing the opened area of single sided ventilation.

Worth to further highlight is the climate's influence on the resulting airflow rates generated by different opening configurations. The fact that the most prominent hourly fluctuations are shown for the case of cross ventilation (Figure 29) suggest that thermal comfort is subject to a higher level of influence by instant changes in local climate conditions than single sided ventilation. I.e, this study demonstrates that ventilation rates generated by cross ventilation are more sensitive to the dynamics of local weather conditions. This is also of importance considering the resulting IAP levels, since temporary low wind speeds in summer were shown to reduce the wind effect (Figure 30) which risk to compromise the performance in providing sufficient airflow rates to ensure a healthy indoor air quality. Reversibly, too strong winds might prevent the cross ventilating window to be opened which also would result in higher IAP levels.

Conclusively, this study suggest that it is vital to include considerations for site-specific characteristics of local climatic conditions in the design and application of alternative opening configurations. This in order to ensure that physical prerequisites as well as behavioral practice allow for sufficient airflow rates for passive ventilation to be successful in preventing accumulation of IAP.

8.2 Overall conclusion

This study confirms that IAP generated from indoor burning of solid biomass fuels risk to be a current problem in the high altitude settlement of Chame, Manang, further indicating that health deteriorating IAP levels might be a continuous problem in similar regions in the Himalayas where biomass dependence prevails. Due to that the extensive reliance on biomass fuels in Nepal as well as in the rest of the developing world is predicted to remain the coming decades, interventions adapted to a continued use of solid biomass are required until energy poverty is eradicated.

There are several attack angles to approach this issue of which the distribution of improved cooking stove (ICS) fitted with chimneys has been the most common intervention strategy the past decade, where both international organizations and the National government are engaged. Intervening at the source of pollution however requires successful implementation programmes in order for IAP levels to be reduced. Training on proper operation and frequent maintenance of the ICS is declared as essential to ensure a healthy indoor air quality. This both for the households who are eligible for the subsidized stoves, as well as for households who have locally manufactured stoves of which several improved features have been observed to be lacking. If the importance of closing the fire gate is not communicated and hence not closed on the subsidized stoves, why would you bother to put a fire gate on the stoves made on site?

Intervening in the living environment is another strategy which includes altering the physical characteristics of the kitchen as well as the behavioral practice of the residents, of which an enhanced natural ventilation has been suggested as one of the most feasible means to reduce IAP levels. This study presents that increasing the ventilation efficiency by providing the building envelope with opening configurations allowing for larger airflow rates, concentrations of IAP can be significantly reduced. Dependent on opening configuration and fraction of fugitive emissions, resulting IAP levels can be ensured below safe limits according to IAQ guidelines presented by WHO as well as Nepalese IAQ standards.

It is nonetheless further confirmed that there is an inverse correlation between ventilation efficiency and indoor thermal comfort. These findings highlight the importance of optimizing passive ventilation strategies with respect to minimizing the accumulation of IAP as well as the impact on thermal comfort. The influence of the surrounding climate on the indoor thermal environment is further illustrated to vary between different opening designs. Consideration to local climatic conditions is hence declared as vital in the development and application of opening designs ensuring for sufficient passive ventilation.

The results presented further confirm that residents in high altitude settlements with similar architectonic features as investigated in this study live far below internationally recognized comfort standards. This is both attributed to inefficient ventilation patterns as well as poor thermal performance of the building envelopes. Energy efficient building techniques improving the utilization and preservation of the available energy is hence predicted to not only reduce the frequency of hours of thermal discomfort. A more stable and comfortable indoor environment resilient to dynamic fluctuations of ambient temperatures is presumed to facilitate the encouragement of residents in high altitude settlements to take advantage of natural ventilation when needed, limiting the trade-off between keeping warm at present versus long term heath impacts resulting from a prolonged exposure to elevated IAP levels. It is however concluded that in order to prevent indoor operative temperatures to fall below 0 ^{o}C during winter, *both* physical parameters of the house construction as well as more efficient passive ventilation strategies would be required.

Understanding the inverse correlation between architecture, natural ventilation, health and indoor thermal comfort hence becomes of great concern in the development of the new Nepalese building standard, initiated by the government in the wake of the devastating earthquake 2015. Except from earthquake resistant house constructions, including aspects of comfort are hereby further requested, where enhancing the thermal performance of the building envelopes would be desirable in high altitude settlements. Nonetheless, if the energy poverty prevails and access to and successful implementation of cleaner cooking technologies do not emerge simultaneously, improving thermal comfort by employing energy efficient building techniques providing airtight homes risk to further aggravate the problematic issue of IAP. This study thus aims to stress the importance of integrating a thorough consideration for the design and application of opening configurations allowing for sufficient natural ventilation in standardized building codes. To conclude, this insight indicates the necessity of having a holistic approach when aiming to improve living conditions within the built environment for biomass reliant households in high altitude regions.

8.2.1 Specific recommendations

To summarize, interventions aiming to reduce IAP levels in biomass reliant households are needed on both the source of pollution as well as in the living environment. For households with opening configurations only allowing for a limited natural ventilation, characteristics of the source of pollution is more important considering stove design and proper operation since these parameters affect the magnitude of fugitive emissions. When it comes to improving indoor air quality by means of passive ventilation, employing cross ventilation reduces IAP levels below safe limits for the widest range of fugitive emissions hence is considered to be the most suitable option in biomass reliant households of high altitudes with similar architectonic features and behavioral practices.

In kitchens with opening configurations not allowing for sufficient air exchange rates during stove usage for the range of fugitive emissions examined, openings need to be kept opened a short while after the stove is extinguished to meet IAQ guidelines for safe health − both in the morning and at night. A more restricted ventilation pattern between stove usage activity is however required for all opening configurations investigated in this study in order to limit the risk for indoor operative temperatures to coincide with ambient temperatures, which today hinder indoor operative temperatures to be maintained above 0 ^{o}C during colder parts of the year.

Opening configurations allowing for sufficient ventilation rates *during* stove usage would thus eliminate the need for keeping openings opened *after* the stove is extinguished, which in turn would reduce the frequency of hours of thermal discomfort. Energy efficient building techniques such as enhancing insulation properties and the thermal mass of the building materials are further presumed to have the potential to enhance indoor thermal comfort in residential houses in Chame.

Informing biomass reliant households about efficient passive ventilation strategies is thereby suggested as a vital step towards improving societal health and well being in high altitude regions in Nepal − considering *both* indoor air quality and thermal comfort. This applies to settlements of which ICS programmes *have* as well as *have not* yet reached and to households with malfunctioning chimney stoves as observed in Chame. This in order to prevent coming years of exposure to slightly or moderately elevated IAP levels which might be hard to visually notice but still risk to pose a substantial threat to public health.

To conclude, building envelopes with an enhanced thermal resistance and opening designs providing adequate prerequisites for passive ventilation are suggested as essential parameters to consider in the new building standard for rural high altitude settlements. This should comprise well-planned opening configurations adapted to the rate of infiltration and local climatic conditions.

8.2.2 Feasibility of interventions

Increasing natural ventilation during stove usage by applying alternative opening configurations to the building envelope would not interfere in the residents regular habits given the consistent correlation found between stove usage and the practice of opening openings. However, the question of feasibility of modifying opening configurations in the vernacular architecture of high altitude settlements remains, given that culture and religion has a great influence in the construction and building layout Nepalese residential units. Additionally, the magnitude of naturally induced airflow rates through the building envelope need not to create other inconveniences in order to be accepted. Moreover, for extended ventilation patterns at night to succeed in kitchens with deficient ventilation rates during stove usage − and a building envelope with a poor thermal resistance − residents need to value the benefits of a better indoor air quality higher than the negative impact on the indoor thermal comfort. This is however highly subjective and thus directly dependent on how the problematic issue of IAP is perceived.

8.3 Personal reflections

8.3.1 Association between energy poverty, architecture, health and environment in societal development

Considering the current lack of access to clean energy services and the predicted continuation of biomass dependence in Nepal the coming decades, improving indoor thermal comfort through passive measures by enhancing the buildings' performance in taking better advantage of the available energy is considered as a clean way of reducing the hours of thermal discomfort in high altitude settlements. This since a reduced need for space heating would reduce fuel consumption and correlated exposure to IAP in high altitude areas where the stove is used also for heating purposes.

Not only is this a question of health equality since women traditionally spend more time in the kitchen hence risk to be exposed to health deteriorating indoor air for longer time periods. A reduced fuel consumption would in turn mitigate the burden of domestic labor for women who today spend a substantial part of the day collecting fuel. Vital to further highlight is that a limited consumption of firewood is of great significance for the ongoing deforestation in Nepal. This is of particular interest in areas of the Himalayas well visited by both national and international trekkers such as the villages along the Annapurna Circuit trek on which Chame is included, since a high level of tourism accelerates fuel consumption.

Enhancing indoor thermal comfort in these areas by integrating energy efficicent building techniques in vernacular architecture is thereby in line with the objectives of ACAP considering the conservation of natural resources as well as the promotion of sustainable social and economic development, thus could be an important complementary strategy to current ICS distribution programs.

The thought of how small interventions in the living environment in Nepalese high altitude settlements can give rise to a cascade of positive effects on several societal levels is fascinating. Due to the complex interconnections between energy poverty and equality, architectural features, IAP levels and correlated health and environmental impacts, this project further exemplifies the essence of a sustainable energy supply and highlights the importance of understanding the role of the association between architecture, energy, health and environment in order to reach a sustainable societal development in Nepal. A visual display of the outlined interdependencies is presented in Figure 41.

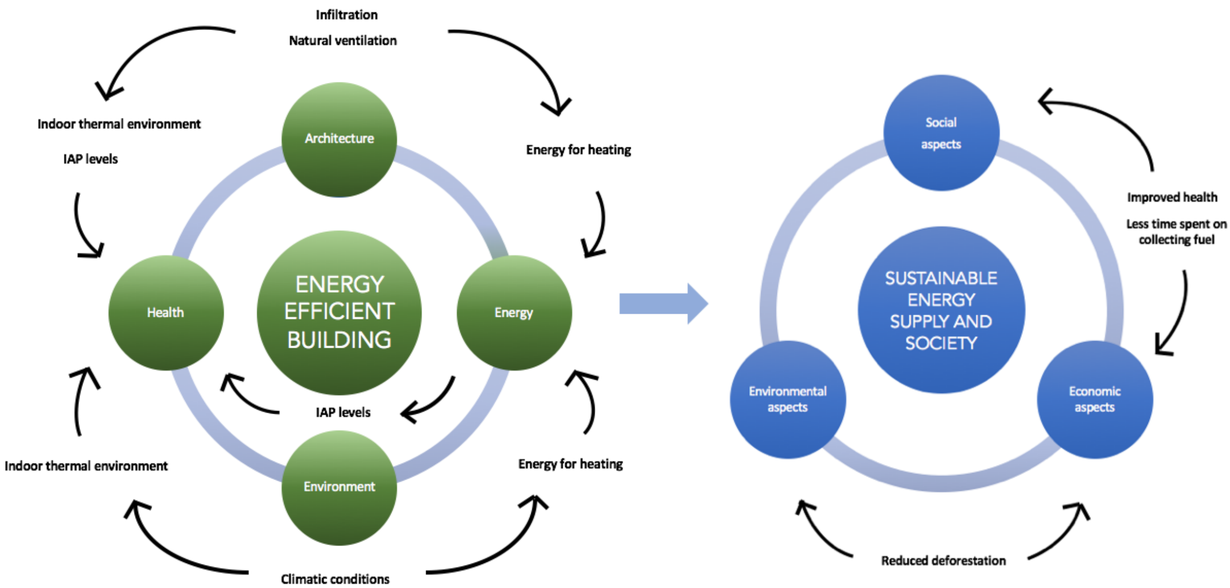

Figure 41: Visual display of the highlighted interconnections between architecture, health, energy demand and environment within the concept of energy efficient building, further linked to the prospects of a sustainable energy supply and a sustainable society: Architectural features determining the magnitude of natural ventilation (i.e. level of infiltration and the design and placement of openings) affect IAP levels as well as indoor thermal comfort – both of which are of great significance for residential health. The physical features of the house construction together with surrounding climatic conditions further determine the energy needed for heating purposes, which in turn impact the risk of exposure to elevated IAP levels. As a warmer indoor climate generated by building envelopes with better thermal performance would reduce the need for additional space heating, health implications associated with indoor burning of solid biomass have the potential to be limited which is crucial for social as well as economic development in Nepal. A reduced firewood consumption is further vital in order to restrain the ongoing deforestation which is of great importance considering the current threat of severe environmental and economic consequences.

8.3.2 Concluding remarks

To conclude, I am well aware of the rather comprehensive information and spread among the topics presented in this thesis. This is however the reason to why I initially decided to take on the challenge to proceed with this project. I am convinced that interdisciplinary research is required in order to get holistic perspectives on complex and intercorrelated societal matters, avoiding to create a cradle for future problems in − what often seem to be feverish − efforts to solve current issues. With that said, I am however humble to the fact that combining different methodologies and research methods within the scope of a master thesis result in limited time to reflect upon the *optimization* of each step regarding selection of research approach, corresponding methods and input parameters.

Given that both the angle of the topic as well as the methods applied were new to both me and my supervisors, there were no strict directives or limits regarding the format of research nonetheless the report. As a result, I created my own limits in the effort to tell my version (of many possible, I am sure) of a story concerning this complex topic with the data I and insights this project gave me during my time in Nepal, resulting in this rather extended master thesis.

I came to be aware of that when going abroad you sign up on that the notorious plan you initially set up will be radically changed, especially when doing field research in form of an interview study. Choosing Chame as site of study came with a more complex analysis of data than predicted for several reasons. Firstly, the fact that almost all of the surveyed households had some kind of ICS became an unexpected turn within the scope of this thesis, when going to Chame in the belief that the majority of the households would be cooking on traditional stoves or open fires indoors. The instant thought of changing the scope was discarded when realizing the complexity with the phenomenon of the ICS and the associated requirements for a successful implementation.

Furthermore, Chame being a somewhat more economically strong village due to tourism, the widespread access to gas stoves, rented housing units and newer house constructions deviating from original vernacular architecture were other parameters needed to be considered in the effort to understand and depict the current situation. Here I came to the conclusion that a categorization of households were required, resulting in the three groups of analysis in the behavioral pattern assessment.

I also learned that conducting step-wise research combining three different methods of which the results from the first step were to be used in the two consecutive steps, requires a well defined and tried pathway in order for the research process to proceed smoothly. Moreover, a combined evaluation of results obtained from two different research pathways (IAP levels and operative temperature in this case) requires a thorough awareness of that the results evaluated might be sensitive to different parameters given that they are derived from different methods.

Given that a part of the aim with this research was to provide *general* stove usage and ventilation profiles valuable for further research on thermal comfort in high altitude settlements in the Himalayas, the interview study and analysis of data were performed quantitatively. This came with the major insight that the approach of using empirical data to display general trends rather than just assessing the situation for *one* household in Chame as in typical case studies, requires a considerably more comprehensive analysis.

In retrospect, using the behavioral profiles on *one* selected household in Chame for the IAP and operative temperature simulations would have reduced the time consuming process of trying to find a representative geometrical base case in line with the research question to *"Assess the current situation"*. Nonetheless, since these two approaches of conducting a case study are fundamentally different both in terms of actual research process as well as the results obtained, it is important to note that this would have changed the scope of this study, now aiming to draw conclusions for a wider range of high altitude settlements.

Consequently, the research process became more prolonged than expected, which has not only resulted in moments of frustration; the battle in the field of finding appropriate methods, input parameters, valid assumptions and discussions of mathematically correct ways of describing reality (e.g. concerning representative averages) have enriched my understanding of the complexity of conducting legitimate research. My aim of finding the *"right"* way to answer the research questions and hypotheses has gradually landed in an acceptance of the following: In a first attempt to describe a phenomenon observed in reality, one has to start with crude assumptions to provide a base from which more refined models can be developed.

As a result, in the aim to present a holistic view on the specific matters of indoor air pollution and thermal comfort, this research process have given me invaluable insights on the interconnection between influencing parameters where both architectonic prerequisites as well as behavioral patterns in Nepalese high altitude settlements are proven to be crucial.

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A Appendix: Interview study

A.1 Questionnaire form

QUESTIONNAIRE:

Stove usage and ventilation pattern in Nepalese households

This questionnaire is a part of an international research study on stove usage, ventilation patterns and thermal comfort in Nepalese households.

By sincerely answering the following questions, you contribute with invaluable information needed in the study. However, participation is **voluntary**. You can **cancel at any time** and the information provided will be treated as **confidential**. Nonetheless, your assistance is highly appreciated.

Signature of interviewer: ………………………… **Date:** ……………........

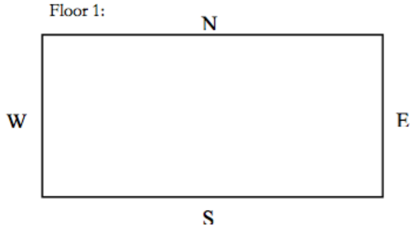
Location of house (Village): ……………………..

Number of family members		**Age of family members**
Adults:	……………	………………………..
Children:	……………	………………………..

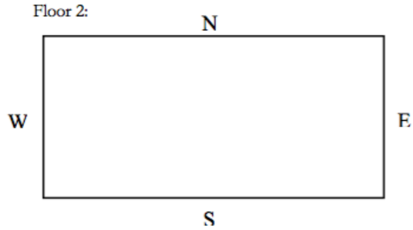
1. Plan of House

In the rectangles below, please illustrate **how many rooms** there are on each floor by drawing **separating lines**. Please specify where the <u>kitchen</u> is by writing a "**K**" in that room. In addition, specify the <u>location of the **stove**</u> in the kitchen by illustrating the shape. Then name the <u>other rooms</u> where <u>people live</u> with numbers by writing **1, 2, 3** etc. in each room.

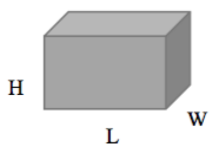
Floor 1:



Floor 2:



2. Kitchen Specification



Kitchen dimensions:
Length (L): …… (m) Width (W): ……. (m) Height (H): …… (m)

Is the kitchen <u>separated</u> from other rooms, enclosed with solid walls? Yes / No

3. Stove, Fuel and Opening Specification

In Table 1 below, please fill in **type of stove** and **fuel** mainly used in the household. Then specify if the stove is equipped with any **ventilation system:**

TABLE 1	**Fuel**	**Exhaust ventilation systems**
Type of stove	Wood/Dung/Agricultural waste/ Charcoal/ LPG / Kerosene /Other	Chimney through roof/ Chimney through wall / None
Traditional Open Firestove		
Improved Stove		
Gas Stove		
Electricity		
Other:		

In Table 2 below, please fill in **type** and **number of openings** in the <u>kitchen</u> by putting a cross **"X"** in the column which specifies orientation. Please also specify **Width (W)** and **Height (H)** in **meters (m)** for each opening in the last column called '*Size*'. If there are several openings with same orientation, name them 1, 2 and/or 3 and specify their respective size under #1, #2 and/or #3:

TABLE 2	**Openings**				**Size (m)**		
Orientation	**Windows**	**Outer Doors**	**Inner Doors**	**Other**	**#1**	**#2**	**#3**
South (S)					W: H:	W: H:	W: H:
West (W)					W: H:	W: H:	W: H:
North (N)					W: H:	W: H:	W: H:
East (E)					W: H:	W: H:	W: H:

If the kitchen is separate, and you can enter by an <u>inner</u> door: is this door constantly open?

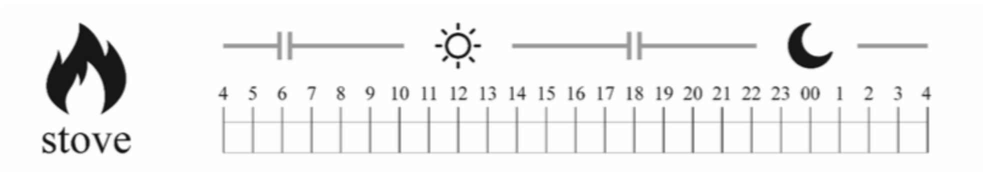
- Yes. Because: ……………………………………………………………………..
- No. Because: ……………………………..…………………………………...

4. Stove Usage and Ventilation Patterns

---- Kitchen -----

Summer

On the timeline below, specify <u>between which hours</u> the **stove is lit in summer** by coloring the boxes corresponding to the correct hours. If the stove is lit more than once per day, mark this on the timeline accordingly.

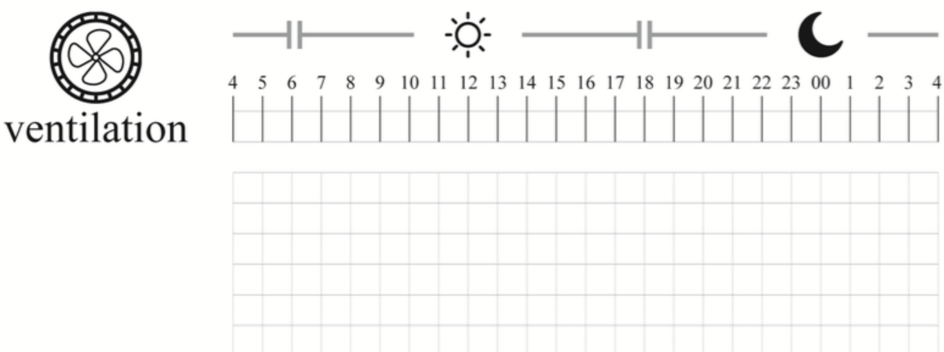


Now please specify between which hours you **ventilate** (i.e. open windows/doors/hole in wall to **let in fresh air**) in **summer** by coloring the correct hours on the time line below.

Please also specify the type of opening, its orientation, and if it is opened "**little**" or "**fully**". If **several openings** are opened, **add one per line** below the time line.

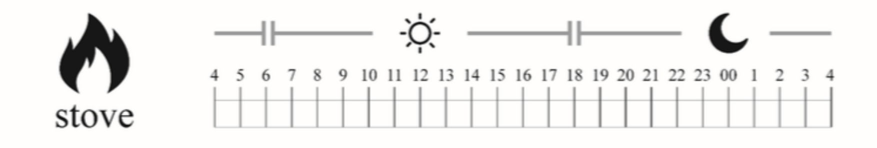
Use the following labels for the opening types:

- Open windows $W_{S/W/N/E}$
- Open doors outer: $oD_{S/W/N/E}$ / inner: $iD_{S/W/N/E}$
- Other type of opening Opening type $_{S/W/N/E}$

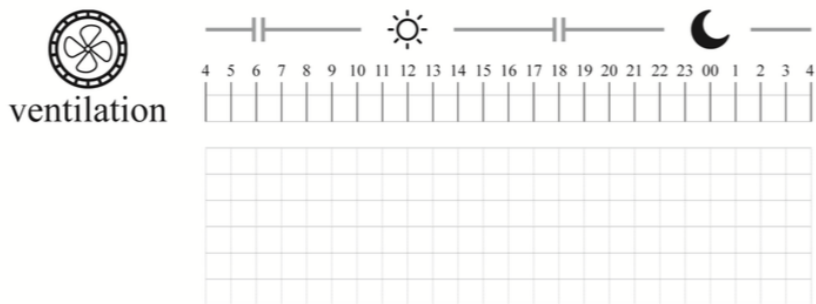


Winter

Please use the same instructions described above to specify **when** the stove is lit in **winter:**



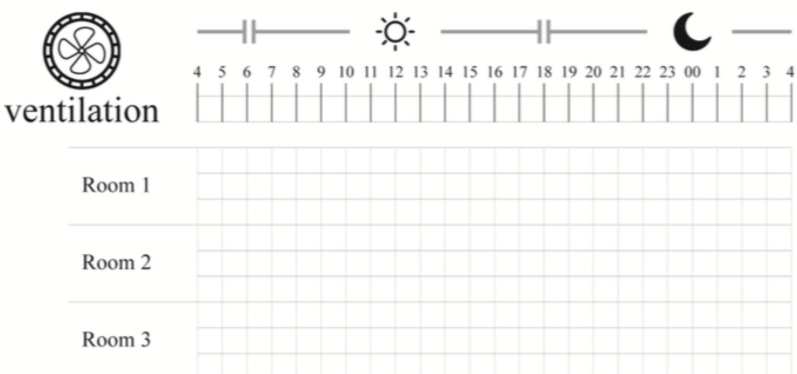
Please use the same instructions described above to specify **when** and **how** you **ventilate** in **winter**:



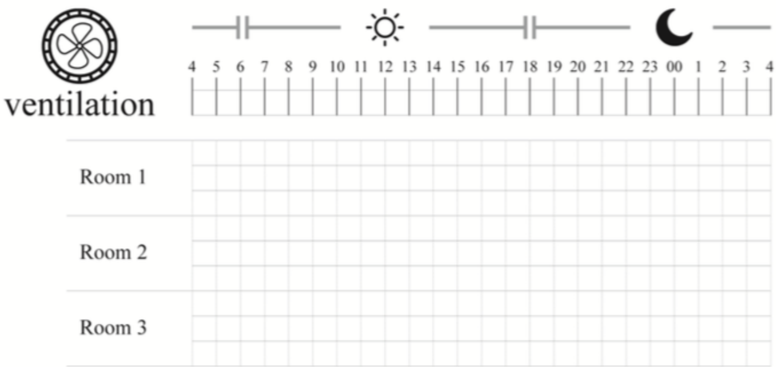
----- Other rooms -----

Please specify **if /when** and **how** you **ventilate** the **other rooms** (room 1, 2, 3 etc.) for both **summer** and **winter** by filling in the time lines below. Please specify one ventilation scheme for **each room** and list **type of openings** below the times colored as described above.

Summer



Winter



If you ventilate other rooms than kitchen, <u>why</u> do you do that?

- To let in fresh air
- To reduce smoke accumulation
- Other: ……………………………………………………………………………………...

1. Ventilation Considerations

When you built your house, did you think of reducing *smoke accumulation* (if solid biomass is used)*/cooking odors* (if no smoke-emitting stove) in the <u>kitchen</u> when designing opening size and opening orientation in the <u>kitchen</u>?

- Yes. Because: ……………………………………………………………………….
- No. Because: ………………………………………………………………………..

When you built your house, did you think of ensuring proper ventilation in the <u>rest of the house</u> when designing opening size and opening orientation?

- Yes. Because: ……………………………………………………………………….
- No. Because: ………………………………………………………………………..

If you do NOT open openings (e.g. windows, doors) in the <u>kitchen</u> to let in fresh air when the <u>stove is used</u>, please specify why:

- Not disturbed by the smoke/cooking odors
- Current ventilation situation (opening size and/or orientation etc.) is non-efficient in reducing smoke/odors
- To limit heat losses
- Other (Specify): ……………………………………………………………………………

2. Personal Opinions of Smoke Exposure

Would you like to reduce the *smoke/cooking odors* in the kitchen if possible?

- Yes. Because: ……………………………………………………………………
- No. Because: ……………………………………………………………………

***If solid biomass used*: Would you like to reduce the smoke in the kitchen by changing stove?**

- Yes. Because: ……………………………………………………………………
- No. Because: ……………………………………………………………………

Do you think increasing opening size and/or create more openings (outside facing widows/doors/other types for natural ventilation) are good solutions to reduce *smoke accumulation/ cooking odors* in the kitchen?

- Yes. Because: ……………………………………………………………………
- No. Because: ……………………………………………………………………

Do you think installing a chimney is sufficient to reduce the *smoke accumulation/ cooking odors* in the kitchen?

- Yes. Because: ……………………………………………………………………
- No. Because: ……………………………………………………………………

3. Materials of Construction

Facades: ………………………………………………………………
Inner walls: ……………………………………………………………
Roof: ……………………………………………………………………
Ceiling: …………………………………………………………………
Floors: …………………………………………………………………

A.2 Results

A.2.1 Opening specification geometrical base case

Number of openings

Table 43: Ranges of most common number of windows assessed for the 13 households having windows.

Windows		
Number of households having windows		13
Range of most common number of windows per household		1 - 3
Relative prevalence [households]		13/13
Specific prevalence [households]	**1**	**10**
	2	3
	3	0

Table 44: Ranges of most common number of windows assessed for the 24 households having outer doors.

Outer doors		
Number of households having outer doors		24
Range of most common number of doors per household		1 - 3
Relative prevalence [households]		24/24
Specific prevalence [households]	**1**	**17**
	2	5
	3	2

Table 45: Ranges of most common number total number of openings assessed for the 24 households having openings facing outside.

Total windows + doors		
Number of households having an opening facing outside		24
Range of most common number of openings per household		1 - 3
Relative prevalence		23/24
Specific prevalence	**1**	7
	2	**11**
	3	5
	5	1

Opening dimensions

Table 46: Specification of width and height of openable openings documented for all 25 households surveyed.

	Opening dimensions openable area					
Reference	Windows		Outer doors		Inner doors	
ALL ORIENTATIONS	W	H	W	H	W	H
1	0,54	1,08	0,8	1,5	0,76	1,7
2	0,5	0,5	0,8	1,65	0,76	1,7
3	1,16	0,9	0,75	2	0,68	1,6
4	0,3	0,5	0,75	2	0,76	2
5	0,45	0,95	0,76	1,5	0,7	2
6	1	0,5	0,8	1,2	0,9	2
7	0,65	1,44	0,8	1,2	0,56	1,82
8	1	1,4	0,84	2	0,8	1,8
9	1,5	1,2	0,65	1,7	0,8	1,8
10	0,8	0,8	0,74	2	0,62	0,95
11	1,5	1,6	0,8	1,9	0,72	1,8
12	1,5	1,6	0,82	2,5	0,72	1,8
13	0,8	0,8	0,8	1,4	0,55	1,65
14	0,58	0,9	0,74	1,9	0,69	1,95
15	0,3	0,5	0,72	2	0,97	1,97
16	0,88	0,91	0,68	1,8	0,5	1,97
17			0,63	1,9		
18			0,6	1,8		
19			0,8	1,8		
20			0,8	1,8		
21			0,8	1,8		
22			0,8	2		
23			0,8	2		
24			0,6	1,8		
25			1	2,16		
26			0,67	2		
27			0,75	1,93		
28			0,6	1,5		
29			0,69	1,95		
30			1,7	1,6		
31			0,6	1,93		
32			0,71	1,92		
33			0,6	1,6		
Absolute number:	16		33		16	
Average dimensions ALL orientations:	**0,84125**	**0,97375**	**0,769697**	**1,810303**	**0,718125**	**1,781875**
Average area ALL orientations:	0,8191672		1,3933848		1,279609	

Table 47: Specification of width, height and area of all openable windows observed.

	Opening dimensions openable area							
	Windows							
	S		W		N		E	
Most common dimensions EASTERN windows:	W	H	W	H	W	H	W	H
2 most common cases:	0,54	1,08	1,16	0,9	1	0,5	1	1,4
Case 1	0,5	0,5	0,3	0,5	0,65	1,44	1,5	1,2
Case 2			0,45	0,95			0,8	0,8
							1,5	1,6
							1,5	1,6
							0,8	0,8
							0,58	0,9
							0,3	0,5
							0,88	0,91
Average dimensions:	0,52	0,79	0,6366667	0,7833333	0,825	0,97	0,9844444	1,0788889
Absolute number of openings:	2		3		2		**10**	
Total area:	0,5832		1,044		0,5		1,4	
	0,25		0,15		0,936		1,8	
			0,4275				0,64	
							2,4	
							2,4	
							0,64	
							0,522	
							0,15	
							0,8008	
SUM:	**0,8332**		**1,6215**		**1,436**		**10,7528**	
Reference								
Average area based on total area:	0,4166		0,5405		0,718		1,07528	
*Large variations in window dimensions of eastern orientation hence standard deviation analysis was preferred over averages								
Average area all orientations:	0,687595							

Table 48: Standard deviation calculations to assess the most common window dimensions for windows with eastern orientation.

Standard deviation calculations for assessment of most common dimensions of easetrn windows

Sample mean (μ)	
Case 1:	2,2
Case 2:	0,6936
Standard deviation (σ)	
Case 1:	0,3464102
Case 2:	0,0928379
CV= σ / μ	
Case 1:	0,1574592
Case 2:	**0,1338494** **CASE 2 BETTER**

Case 1:	W	H	X (area)	(X- μ)^2
	1,5	1,6	2,4	0,04
	1,5	1,6	2,4	0,04
	1,5	1,2	1,8	0,16
SUM:				0,24

Case 2:	W	H	X (area)	(X- μ)^2
	0,8	0,8	0,64	0,00287296
	0,8	0,8	0,64	0,00287296
	0,88	0,91	0,8008	0,01149184
SUM:				0,01723776

Which dimensions to choose?		
Standard Error of the mean value	0,0536	
Tabulated value	1,96	
95 % confidence interval HIGHER VALUE of area	**0,798656**	Max value of mean that exist. Max value chosen since Case 1 (the other area candidate) represents a larger area.

Which dimensions to choose within dimensions presented in Case 2?

The dimensions which correspond best to the higher value of mean area (where standard error is included):

0,8 * 0,8	0,64
0,88 * 0,91	**0,8008**
BASE CASE WINDOW DIMENSIONS	**0,9 * 0,9**
Opening area:	**0,81**

*Corresponds well to average area of windows of all orientations

Table 49: Specification of width, height and area of all outer doors observed.

	Opening dimensions openable area							
	Outer doors							
	S		W		N		E	
Most common dimensions EASTERN doors:	W	H	W	H	W	H	W	H
	0,76	1,5	0,75	2	0,8	1,5	0,84	2
Common dimensions	0,8	1,2	0,65	1,7	0,8	1,65	0,74	2
	0,63	1,9	0,8	1,4	0,75	2	0,8	1,9
	0,8	1,8	0,72	2	0,8	1,2	0,82	2,5
	0,6	1,8	0,6	1,8	0,68	1,8	0,74	1,9
	0,6	1,5	0,8	1,8	0,67	2	0,8	1,8
	0,69	1,95	0,8	2	1,7	1,6	0,8	2
	0,6	1,93	1	2,16	0,6	1,6	0,75	1,93
	0,71	1,92						
Absolute number of openings:	9		8		8		8	
Average dimensions:	0,6877778	1,7222222	0,765	1,8575	0,85	1,66875	**0,78625**	**2,00375**
Area based on average dimensions:	1,1845062		1,4209875		1,4184375		**1,5754484**	
Total area:	1,14		1,5		1,2		1,68	
	0,96		1,105		1,32		1,48	
	1,197		1,12		1,5		1,52	
	1,44		1,44		0,96		2,05	
	1,08		1,08		1,224		1,406	
	0,9		1,44		1,34		1,44	
	1,3455		1,6		2,72		1,6	
	1,158		2,16		0,96		1,4475	
	1,3632							
SUM:	**10,5837**		**11,445**		**11,224**		**12,6235**	
Reference								
Average area based on total area:	1,1759667		1,430625		1,403		**1,5779375**	

A.2.2 Adjustment of opening dimensions applied in the base case model

Table 50: Adjustment of opening widths to correspond to the actual area opened obtained from the ventilation pattern assessment.

Base Case opening area: Adjustment of opening widths					
SUMMER					
If same width of window and door:	1,30 = x* 2 + x * 0,9				**CHECK:**
	width = x =	0,448	**0,4**		1,3
WINTER					
If same width of window and door:	1,06 = x* 2 + x * 0,9				**CHECK:**
	width = x =	0,366	**0,4**		1,06

A.2.3 Ventilation practices: employment of cross ventilation

Table 51: Specification of prevalence of households taking advantage of cross ventilation.

Employment of cross ventilation		
Opening prerequisites	Prevalence [households]	
Possibility to cross ventilate	8	
Possibility to side ventilate	5	
Possibility to use both cross and side ventilation (included in both side and cross)	3	
Employment of ventilation: Summer	Prevalence [households]	%
Cross ventilation	5	62,5
Side ventilation	4	80,0
Cross + side ventilation	2	66,7
Side ventilation only	2	100,0
Employment of ventilation: Winter		
Cross ventilation	4	50,0
Side ventilation	1	20,0
Cross + side ventilation	1	33,3
Side ventilation only	0	0,0

A.2.4 Stove usage and ventilation correlation

General case: all stove types included

Table 52: Specification of stove usage and ventilation practices and their inter-correlation during summer.

All households	SUMMER		
Total number of households = 22	MORNING	AFTERNOON	WHOLE DAY
Number of households using their stove	21/22 (95 %)	22/22 (100 %)	0
Number of households who use the stove but do not open openings	1/21 (5 %)	1/22 (4,5 %)	
Number of households who open openings when not using the stove	1/21 (5 %)	1/22 (4,5 %)	
Number of housholds who neither use the stove nor open openings	1/22 (4 %)	0	
Number of households who open openings when stove is used	19/21 (90 %)	20/22 (90,9 %)	
Only during stove usage	8/19 (42 %)	9/20 (45 %)	
During stove usage and whole day	11/19 (58 %)	11/20 (55 %)	

Table 53: Specification of stove usage and ventilation practices and their inter-correlation considering point in time and duration of each activity during summer.

All households	SUMMER	
Total number of households = 22	MORNING	AFTERNOON
Number of households using stove and open openings during stove usage	19/22 (86 %)	20/22 (91 %)
Opening openings		
Openings opened when stove is lit	18/19 (95 %)	9/20 (45 %)
Openings opened during stove usage	1/19 (5 %)	0
All day ventlilators		11/20 (55 %)
Closing openings		
When stove is exinguished	8/19 (42 %)	18/20 (90 %)
Before stove is extinguished	0	1/20 (5 %)
After stove is extinguished	0	1/20 (5 %)
All day ventlilators	11/19 (58 %)	

Table 54: Specification of stove usage and ventilation practices and their inter-correlation during winter.

All households	WINTER		
Total number of households = 22	MORNING	AFTERNOON	WHOLE DAY
Number of households using their stove	21/22 (96 %)	19/22 (86 %)	4/22 (18 %)
Number of households who use the stove but do not open openings	2/21 (10 %)	2/19 (10 %)	
Number of households who open openings when not using the stove	0	0	
Number of housholds who neither use the stove nor open openings	1/22 (4 %)	3/22 (14 %)	
Number of households who open openings when stove is used	19/21 (90 %)	17/19 (90 %)	
Only during stove usage	9/19 (47 %)	7/17 (41 %)	
During stove usage and whole day	10/19 (53 %)	10/ 17 (59 %)	
Number of households who have the stove lit all day			4/22 (18 %)
of which keep opening opened the whole time			4/4 (100 %)
of which keep openings opened part of the time			0

Table 55: Specification of stove usage and ventilation activities and their inter-correlation considering point in time and duration of each activity during winter.

All households	WINTER	
Total number of households = 22	MORNING	AFTERNOON
Number of households using stove and open openings during stove usage	19/22 (86 %)	17/22 (77 %)
Opening openings		
Openings opened when stove is lit	19/19 (100 %)	7/17 (41 %)
Openings opened during stove usage	0	0
All day ventlilators		10/17 (59 %)
of which are all day stove users		4 /17 (24 %)
Closing openings		
When stove is exinguished	9/19 (47 %)	16/17 (94 %)
Before stove is extinguished	0	1/17 (6 %)
After stove is extinguished	0	0
All day ventlilators	10/19 (53 %)	
of which all day stove users	4/10 (40 %)	

ICS users only

Table 56: Specification of stove usage and ventilation practices and their intercorrelation during summer.

ICS users only	SUMMER		
Total number of households = 12	MORNING	AFTERNOON	WHOLE DAY
Number of households using their stove	11/12 (92 %)	12/12 (100 %)	0
Number of households who use the stove but do not open openings	1/11 (9 %)	1/12 (8 %)	
Number of households who open openings when not using the stove	0	0	
Number of housholds who neither use the stove nor open openings	1/12 (8 %)	0	
Number of households who open openings when stove is used	10/11 (91 %)	11/12 (92 %)	
Only during stove usage	4/10 (40 %)	5/11 (46 %)	
During stove usage and whole day	6/10 (60 %)	6/11 (54 %)	

Table 57: Specification of stove usage and ventilation practices and their intercorrelation considering point in time and duration of each activity during summer.

ICS users only	SUMMER	
Total number of households = 12	MORNING	AFTERNOON
Number of households using stove and open openings during stove usage	10/12 (83 %)	11/12 (92 %)
Opening of openings		
Openings opened when stove is lit	10/10 (100 %)	5/11 (46 %)
Openings opened during stove usage	0	0
All day ventlilators		6/11 (54 %)
Closing openings		
When stove is exinguished	4/10 (40 %)	10/11 (91 %)
Before stove is extinguished	0	1/11 (9 %)
After stove is extinguished	0	0
All day ventlilators	6/10 (60 %)	

Table 58: Specification of stove usage and ventilation practices and their inter-correlation during winter.

ICS users only	WINTER		
Total number of households = 12	MORNING	AFTERNOON	WHOLE DAY
Number of households using their stove	12/12 (100 %)	11/12 (92 %)	3/12 (25 %)
Number of households who use the stove but do not open openings	1/12 (8 %)	1/11 (9 %)	
Number of households who open openings when not using the stove	0	0	
Number of housholds who neither use the stove nor open openings	0	1/12 (8 %)	
Number of households who open openings when stove is used	11/12 (92 %)	10/11 (91 %)	
Only during stove usage	6/11 (54 %)	5/10 (50 %)	
During stove usage and whole day	5/11 (46 %)	5/10 (50 %)	
Number of households who have the stove lit all day			3/12 (25 %)
of which keep opening opened the whole time			3/3 (100 %)
of which keep openings opened part of the time			0

Table 59: Specification of stove usage and ventilation activities and their inter-correlation considering point in time and duration of each activity during winter.

ICS users only	WINTER	
Total number of households = 12	MORNING	AFTERNOON
Number of households using stove and open openings during stove usage	11/12 (92 %)	10/12 (83 %)
Opening of openings		
Openings opened when stove is lit	11/11 (100 %)	5/10 (50 %)
Openings opened during stove usage	0	0
All day ventlilators	0	5/10 (50 %)
of which are all day stove users		3/5 (60 %)
Closing openings		
When stove is exinguished	6/11 (54 %)	10/10 (100 %)
Before stove is extinguished	0	0
After stove is extinguished	0	0
All day ventlilators	5/11 (46 %)	
of which all day stove users	3/5 (60 %)	

A.2.5 Stove usage patterns and profiles

General case: all stove types included

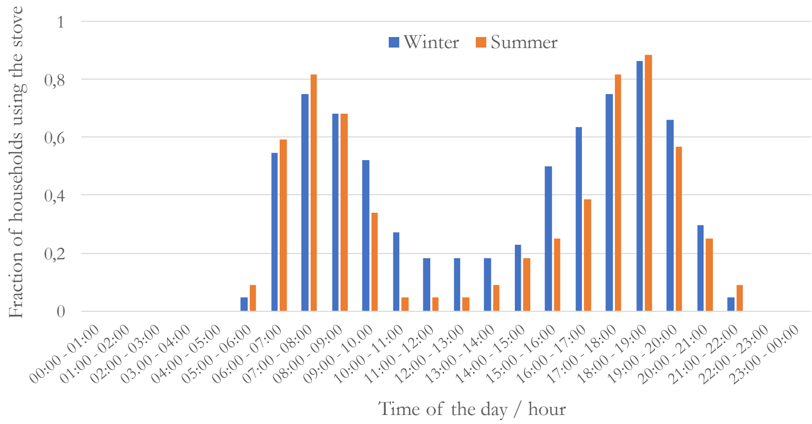


Figure 42: Seasonal stove usage patterns displaying the percentage of households using the stove a certain hour.

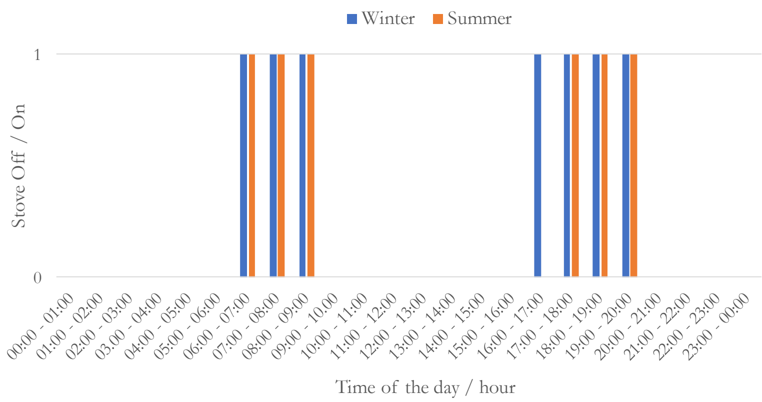


Figure 43: Seasonal stove usage profiles representing general practice considering duration and point in time of using the stove. Compatible as occupant behavior input parameters in simulation tools such as DEROB.

ICS users only

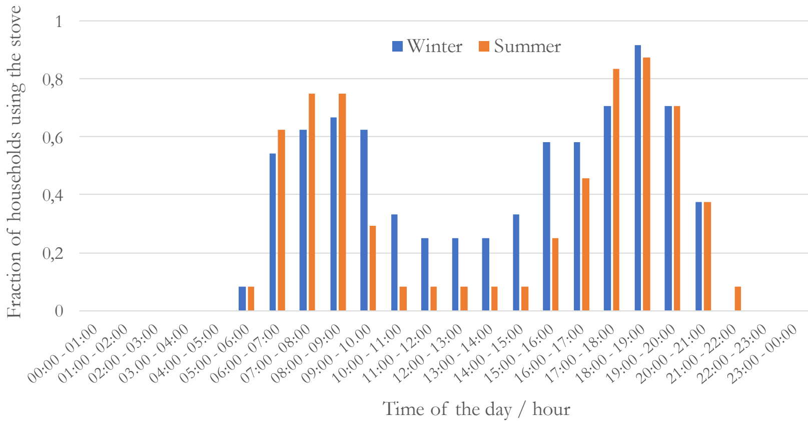


Figure 44: Seasonal stove usage patterns displaying the percentage of households using the stove a certain hour.

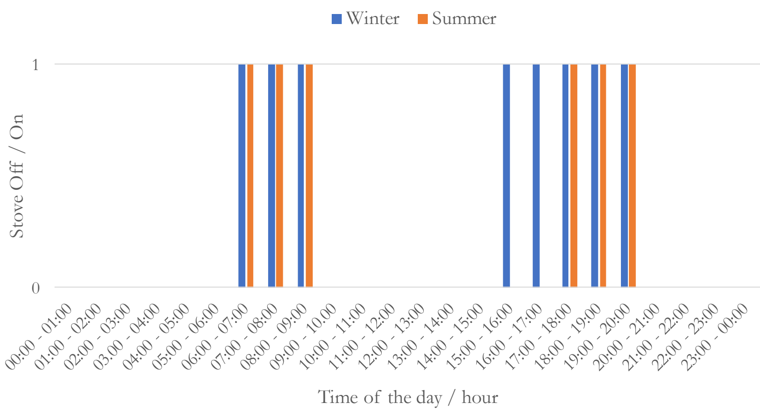


Figure 45: Seasonal stove usage profiles representing general practice considering duration and point in time of using the stove. Compatible as occupant behavior input parameters in simulation tools such as DEROB.

A.2.6 Ventilation patterns and profiles

General case: all stove types included

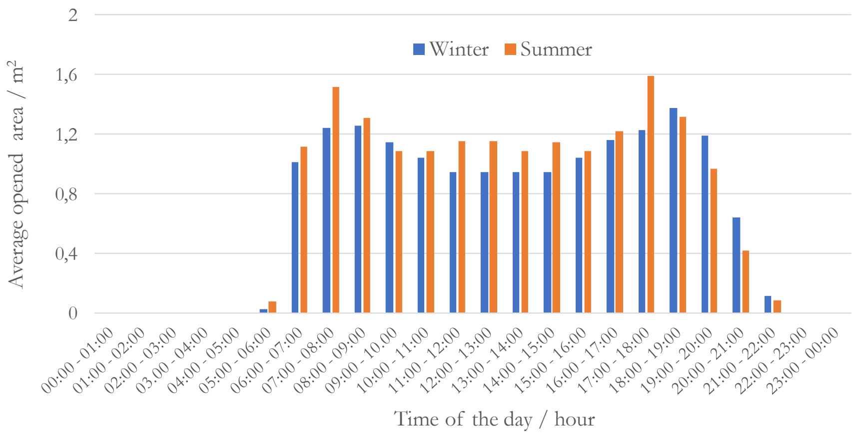


Figure 46: Seasonal ventilation patterns displaying average area opened per hour.

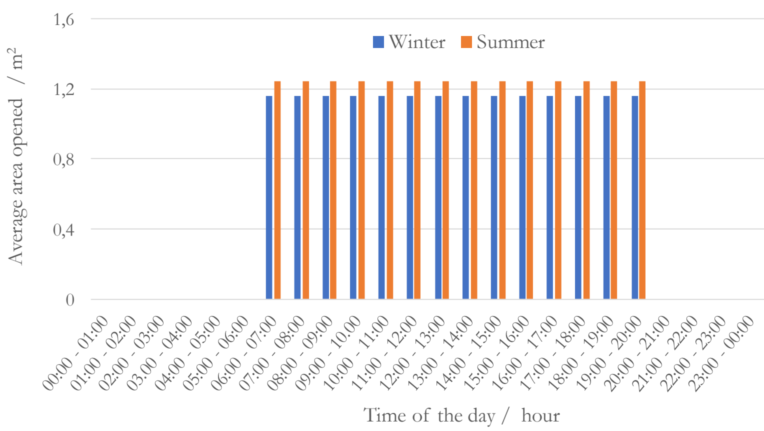


Figure 47: Seasonal ventilation profiles representing general practice of employing natural ventilation considering area opened per hour. Compatible as occupant behavior input parameters in simulation tools such as DEROB.

ICS users only

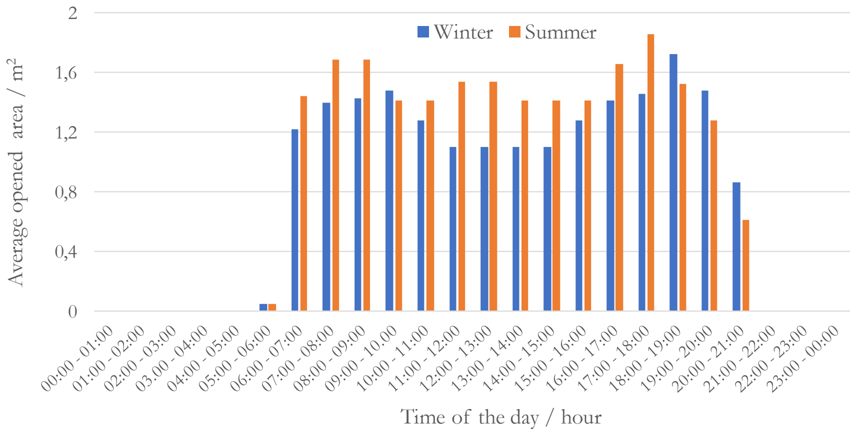


Figure 48: Seasonal ventilation patterns displaying average area opened per hour.

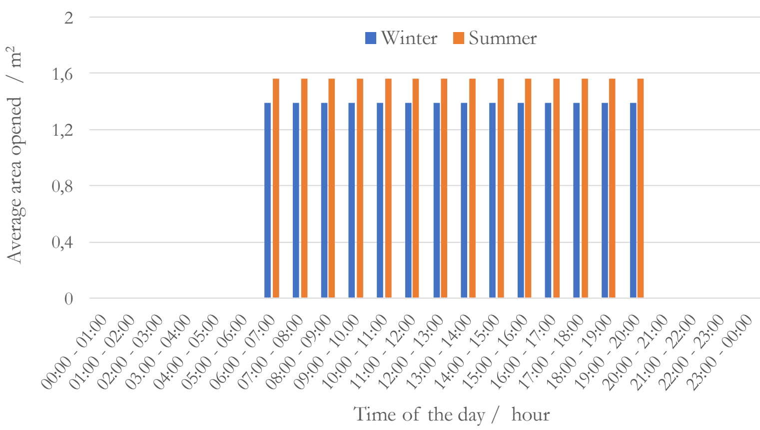


Figure 49: Seasonal ventilation profiles representing general practice of employing natural ventilation considering area opened per hour. Compatible as occupant behavior input parameters in simulation tools such as DEROB.

B Appendix: DEROB simulation specifications

B.1 Material specification of DEROB model

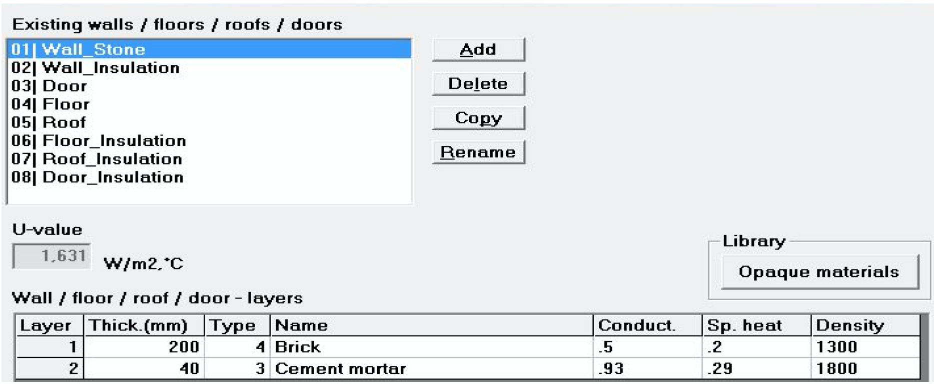


Figure 50: Specification of thermal properties and thickness of wall materials applied in the DEROB simulation models.

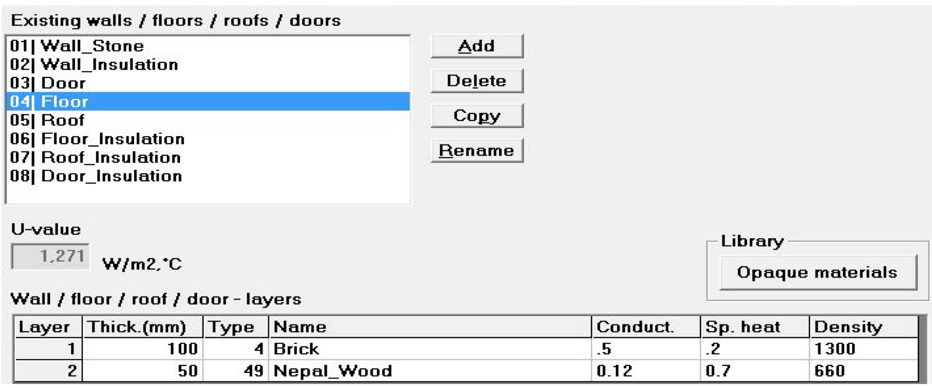


Figure 51: Specification of thermal properties and thickness of floor materials applied in the DEROB simulation models.

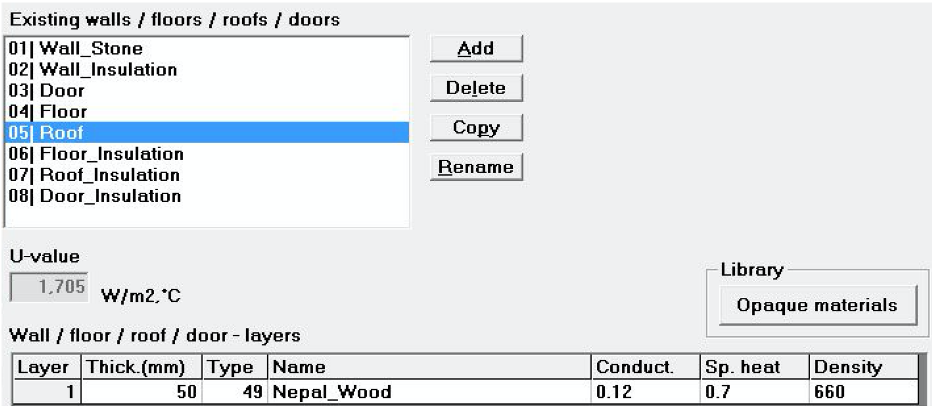


Figure 52: Specification of thermal properties and thickness of the roof material applied in the DEROB simulation models.

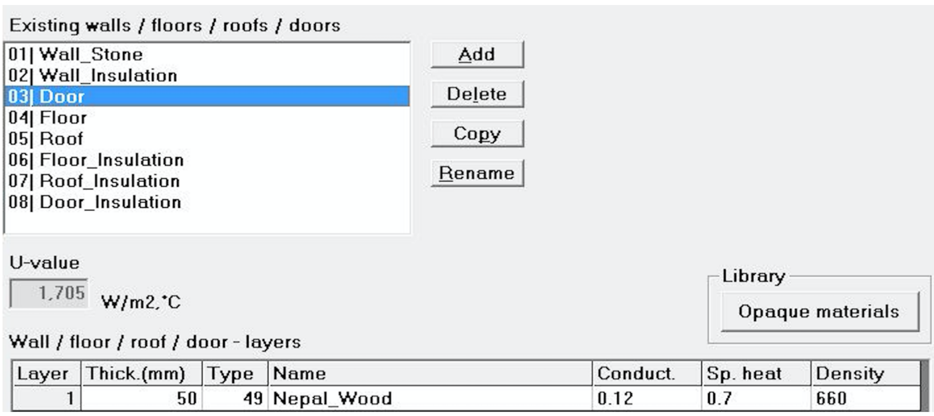


Figure 53: Specification of thermal properties and thickness of the door material applied in the DEROB simulation models.

B.2 Validation of DEROB model

The DEROB model employed for both airflow calculations and operative temperature simulations was validated by a standardized validation process to verify model reliability. The standardized DEROB validation routine comprise the following steps:

1. **Physical model view**
   DEROB provides a 3D view of the model where the physical features such as building element placement, size and orientation of openings can be visually validated.

2. **Empirical validation: Insolation**
   The orientation of the model was validated by investigating the influence of diurnal solar angles by checking the temperature of the outer walls for different times of the day. The insolation on transparent surfaces was further examined. Considering the incoming solar radiation reaching the transparent surface as 100 %, the fraction *transmitted* into the volume and *absorbed* by the volume should be 90 % and 80 % respectively as a rule of thumb. Hence, the incoming and absorbed solar radiation should be similar in order of magnitude.

3. **Analytic verification: Heat loss and heat gain balance**
   Heat balances of the model were checked by verifying simulated heating loads (in watts, W) required to maintain 20 ^{o}C with hand calculations of the required heating load based on the overall heat transfer coefficient (U_A-value) for all building elements. Moreover, heat losses resulting from an increased airflow were similarly verified by comparing simulated values of the additional heat required to maintain 20 ^{o}C with hand calculations for a set active ventilation rate.

B.3 DEROB as an airflow simulation tool

Single sided ventilation and wind directions
The wind directions of 45^o, 135^o, 225^o and 315 ^{o} did not show different ventilation rates for the opening configuration cases with single sided ventilation. This since these winds fall towards the house with the same angle and DEROB only calculates the resulting air flow due to pressure difference between the indoor and outdoor environment. Thus, there is no difference in inflow or outflow for these wind directions even if there is more opened area on the eastern side. However, DEROB does acknowledge the fact that there is more opened area exposed for wind on eastern side by balancing the ratio between natural ventilation and infiltration: for an angle of 45^o or 135^o the natural ventilation fraction of the total inflow is much bigger than for 225^o and 315^o, where the total inflow is balanced by a 10 times larger infiltration. AER models which consider the respective influence from leakage on the resulting airflow rates increase the understanding of the individual contributions from leakage and natural ventilation respectively (Breen et al. 2014). Moreover, as the air exchange due to leakage is largest for hot as well as cold days (Breen et al. 2014), DEROB can be helpful with determining the influence of leakage for specific climate conditions.

B.3.1 Validation of accuracy

An extensive validation process of using DEROB as an airflow simulation tool run with modified climate files was conducted since this program had not previously been employed exclusively for this purpose. The theory of stack effect was tested by simulating a lower internal heat gain and leakage parameter (2 000 W and 2 $l/s/m^2$ respectively) for the case of single sided ventilation. The dynamic influence of ambient temperature was clearly shown: the smaller temperature difference between indoor and outdoor air, the lower ventilation rate, being in accordance with the theoretical explanation of stack effect.

The difference in ventilation rates between low and high ambient temperatures (-15 ^{o}C vs. 25 ^{o}C) was further confirmed to be highest for low wind speeds. This in line with the fundamental theory on natural ventilation since the stack effect has a more prominent influence on resulting airflow rates when wind speeds are low.

C Appendix: Airflow rate simulations and IAP calculations

C.1 Input parameters

C.1.1 Fuel burning rate

Table 60: Summary of fuel burning rates (F) for different metallic stove types reported in literature upon which the average F of 2 kg/h used in the calculations and simulations is based.

Source	Country	Stove type	kg/h
Nepal Energy Efficiency Programme (NEEP) (2011)	Nepal	Metallic (chimney)	1.3
Fuller, Zahnd, and Thakuri (2009)	Nepal	Metallic (chimney)	2.5
Thakuri S. (2006)	Nepal	Metallic (chimney)	2.9
Zhang et al. (1999b)	General developing countries	Metallic	1.7

C.1.2 Calorific value of firewood

Table 61: Summary of lower heating values (LHV) of firewood reported in literature upon which the LHV of 17 MJ/kg used in the calculations and simulations is based.

Source	Country	Stove type	Calorific value / (MJ/kg)
Fuller, Zahnd, and Thakuri (2009)	Nepal	Metallic (chimney)	15
Jetter et al. (2012)	-	General for standard comparison	17.7

C.2 Histogram clarifications

In the histogram-based assessment of weighted annual average airflow rates resulting from each opening configuration case, the borders for the histogram ranges were defined to only include the lower limit. As an example, for the range of wind directions between $0^o - 30^o$, the airflow rates generated for the wind direction of 0^o are included but not 30^o ([0; 30 [). This since the wind speeds resulting from 360^o were added to the column of wind speeds calculated for the direction of 0^o (DEROB provides output data for both for 0^o and 360^o). For consistency, the borders for the temperature based histograms were defined accordingly.

As a sensitivity analysis, the influence of including the airflow rates generated by the upper limit of the histogram ranges instead was tested for the base case with the temperature based histogram. The difference in weighted average airflow rate obtained resulted in 0.08 l/s (217.49 l/s vs. 217.57 l/s).

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