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A Comparative Study of Different Improved Cooking Stoves in Nepal: Assessing Fuel Diversity Efficiency and Marginal Abatement Costs

by

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ABSTRACT

In Nepal, traditional stoves, predominantly used in rural areas, have raised significant concerns, including heightened fuel consumption, indoor air pollution, and deforestation. Recently, Improved cooking stoves (ICS) have emerged as a promising alternative, showcasing remarkable reductions in fuel usage and emissions while improving cooking efficiency and indoor air quality. This research aims to comprehensively evaluate commercially available high-efficiency ICS across critical parameters. The study evaluated the performance and economic viability of various wood and charcoal-burning stoves, considering their thermal efficiencies, emission reduction capabilities, net present values (NPVs), internal rates of return (IRRs), benefit-cost (B-C) ratios, and marginal abatement costs. Among the stove types assessed, the force draft wood stove utilizing firewood emerged as the most economically advantageous option, despite its lower thermal efficiency compared to other fuels. Despite its lower efficiency, this stove demonstrated the highest NPV of NPR. 3600, an impressive IRR of 80%, and a commendably low marginal abatement cost of NPR. 748 per ton of CO_2 equivalent. The findings underscored the significance of considering factors beyond thermal efficiency alone, highlighting the pivotal role of economic feasibility, emission reduction potential, and long-term financial returns in assessing the suitability of cooking stoves, wherein the firewood-powered stove showcased robust economic viability and considerable environmental benefits.

Additionally, the study elucidated distinct trends in stove performance metrics, elucidating the trade-offs between efficiency, emissions, and economic returns. While force draft wood pellet stoves exhibited high thermal efficiency, their economic feasibility was marred by negative NPVs and higher marginal abatement costs, emphasizing their limited viability despite efficiency gains. Conversely, despite lower efficiencies, charcoal and firewood-powered stoves demonstrated higher economic returns, emphasizing the pivotal role of factors like fuel cost, NPV, and emission reduction potential in evaluating stove performance comprehensively. This comprehensive analysis sheds light on the intricate interplay between stove efficiency, economic viability, and environmental impact, ultimately accentuating the significance of a multifaceted approach in selecting cooking stoves that balance efficiency gains with economic and environmental sustainability.

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LIST OF SYMBOLS

C_0	Total Initial investment cost
C_t	Net Cash Flow during time period t
EJ	Exajoule
g	Gram
g/ltr	Gram Per liter
i	Discount Rate
kJ	Kilo Joules
l	Liters
mg	Milligrams
R_t	Net Cash Flow

LIST OF ABBREVIATIONS

B-C Ratio	Benefit Cost Ratio
CDM	Clean Development Mechanism
CO	Carbon monoxide
CO_2	Carbon dioxide
GHGs	Green House Gases
ICS	Improved Cooking Stoves
IRR	Internal Rate of Return
LPG	Liquified Petroleum Gas
MAC	Marginal Abetment Cost
MIRR	Modified Internal Rate of Return
NCV	Net Calorific Value
NIBC	Nepal Interim Benchmark for Solid Biomass Cookstove
NPV	Net Present Value
PM 2.5	Particulate Matter 2.5
RETS	Renewable Energy Test station
TCS	Traditional Cooking Stove
WHO	World Health Organization

CHAPTER ONE: INTRODUCTION

1.1 Background

In Nepal, millions of people, especially in rural areas, rely on traditional stoves for cooking, which often leads to increased fuel consumption, indoor air pollution and deforestation (WHO, Household Air Pollution, 2022). In recent years there has been growing interest in using ICS as a more efficient and sustainable alternative to traditional stoves. ICS have been shown to significantly reduce fuel consumption and emissions while improving cooking efficiency and indoor air quality. Energy demand of people living in rural areas of Nepal is primarily dependent in biomass resources. About 80% of the total populations of Nepal utilize biomass as a primary source of energy for cooking. (Nepal, 2013). According to World Bank report 2011, Improved Cooking Stove (ICS) is a stove that is designed to improve energy efficiency, lessen indoor air pollution, or lessen the time spent for cooking. Major benefits of ICS include increased thermal efficiency, less fuel wood consumption leading to reduced pressure on forest, clean indoor environment, convenience in cooking and cutting down the greenhouse gas emission. It reduces drudgery especially for woman and children, prevention of fire hazards. Some of the field test and measurement has shown that ICS saves about 50% fuel than traditional ones and reduces emission considerably (Adhikhari, 2020).

Improved Cookstoves are characterized by their high thermal efficiency, which is typically around 30-40%, compared to traditional stoves that may have an efficiency of only 10-20%. This is achieved through a combination of design features, such as an insulated combustion chamber, a vertical chimney, and a secondary air intake that allows for complete combustion of the fuel. ICS are particularly well-suited for use in rural areas of developing countries, where access to electricity and modern cooking fuels is limited. In recent years, there has been growing interest in promoting the use of cookstoves as a sustainable and affordable solution for household cooking and heating. In addition to their high efficiency, ICS also have several other benefits. They produce very little smoke and other harmful emissions, which can improve indoor air quality and reduce the risk of respiratory diseases. They also require much less fuel than traditional stoves, which can reduce deforestation and save households money on fuel costs. Finally, ICS are relatively easy to build and maintain, using locally available materials and simple construction techniques.

Traditional biomass, such as wood, agricultural leftovers, municipal waste, etc., contributes to around 10% of the world's energy production, and 55% of that energy is used for residential uses (cooking and heating).

The Scenario of Nepal is no different. The overall amount of energy consumed in 2021 was 626 PJ, and conventional energy sources still dominated the energy mix. The share of these conventional fuels has, however, noticeably decreased over time. Traditional biomass, the most widely used fuel, made up 66% of the energy mix in 2021, down significantly from 87% in 2009. This change reflects a definite movement in favor of cleaner energy sources.

The consumption of fuelwood has exhibited the fastest rate of development among conventional energy sources, whereas the use of animal waste has fallen from 5.7% in 2009 to 2.87% in 2021. A rise in the proportion of business energy use has also occurred, going from 12% in 2009 to over 31% in 2021. This implies This shows that in terms of overall energy usage, there is a rising reliance on contemporary energy sources. (Nepal Energy Sector Synopsis Report , 2022)

In Nepal, about 69% of the population lack access to clean cooking facilities and it reaches to more than 80%in rural areas. They mainly rely on solid fuels like wood (89%), animal dung (7%), agricultural residues (4%) etc. for daily cooking. In Nepal, HAP results in the death of 18000 people yearly and can be linked to many cases of chronic obstructive pulmonary diseases, stroke, lung cancer and many other health related issue (Nepal Energy Sector Synopsis Report , 2022). Nepal's energy and cooking context is characterized by a heavy reliance on traditional biomass cooking methods, such as open fires and inefficient stoves. According to the International Energy Agency, more than 80% of Nepal's population relies on traditional biomass for cooking (IEA, 2020). This has significant health and environmental consequences, as indoor air pollution from burning biomass is a leading cause of premature death and illness in Nepal (WHO, Household air pollution and health, 2016). To address this issue, there have been efforts to promote cleaner and more efficient cooking technologies, in Nepal. improved cookstoves have shown promising results in reducing fuel consumption and indoor air pollution while also being cost-effective and easy to use (Shrestha, 2016).

1.2 Problem Statement

The use of traditional cooking methods in many developing regions leads to significant fuel inefficiency, high emissions, and adverse health and environmental impacts. Nepal is highly dependent on biomass especially in residential area. Around 80% of rural area is dependent on biomass. Unplanned biomass gathering and ineffective burning of this biomass using conventional cooking methods are serious issues since they have a negative impact on the environment and human health. It is impractical to replace the traditional cooking system with Modern Cooking system as it changes the habit of the people. Improved stoves have emerged as a promising alternative, offering improved fuel efficiency and reduced emissions. Teir 3 ICS have become a promising technology in the search for environmentally friendly cooking and heating options since they provide improved energy efficiency. However, it might be difficult to choose the most efficient and suitable configuration for particular applications and localities due to the diversity of improved cooking stove designs, materials, and building methods. A comparative analysis of several cooking stove types is urgently needed to determine the most effective, economical, and environmentally friendly designs in order to encourage the wider use of ICS and optimize their advantages.

In Nepal, various types of cooking stoves designed for different fuel sources are utilized without a comprehensive comparative evaluation. The is need of such comparative analysis impedes informed decision-making for stove selection, construction, and optimization for local needs. The correlations between stove efficiency, specific fuel consumption, emissions, and economic viability of ICS models is essential for the identification of optimal stove choices and fuels for sustainable cooking practices.

1.3 Objectives

The main objective is to compare the fuel diversity, efficiency, and evaluate marginal abatement cost of different improved cooking stoves in Nepal for comprehensive comparative analysis

Specific objectives of the study are

- To measure and compare the thermal efficiency and combustion completeness of selected Improved Cookstove (ICS)
- To evaluate the environmental impact by analyzing emissions and fuel consumption for different cookstove configurations
- To perform Financial Analysis of stove designs suitable for specific contexts and applications
- To calculate the Marginal Abetment Cost for different improved cookstove configuration.

1.4 Limitations

The limitation of this study are as follows

- The sample size of the stove is small for the study.

- The experiment for emission test with different fuel couldn’t be performed due to limited resources which would help to provide emission of different fuels.
- Testing condition with limited variability of fuel might not represent the whole context.

CHAPTER TWO: LITERATURE REVIEW

The use of biomass resources for cooking and heating is as old as human civilization. Currently, more than 3 billion people in the world rely on biomass for cooking and space heating purposes. (Ayush Parajuli, 2019). Biomass is often considered as a renewable energy source to reduce fossil fuel emissions, especially in sectors of the economy that are hard to decarbonize, such as aviation. Broadly, solid biomass is defined as "any plant matter used directly as fuel or converted into other forms before combustion (Glossary of Stat). Biomass is renewable organic material that comes from plants and animals. Biomass contains stored chemical energy from the sun that is produced by plants through photosynthesis. Biomass can be burned directly for heat or converted to liquid and gaseous fuels through various processes (www.eia.gov, 2023). In 2020 biomass produced 58 EJ (exajoules) of energy, compared to 172 EJ from crude oil, 157 EJ from Charcoal, 138 EJ from natural gas, 29 EJ from nuclear, 16 EJ from hydro and 15 EJ from wind, solar and geothermal combined. Approximately 86% of modern bioenergy is used for heating applications, with 9% used for transport and 5% for electricity. Most of the global bioenergy is produced from forest resources. The IEA's Net Zero by 2050 scenario calls for traditional bioenergy to be phased out by 2030, with modern bioenergy's share increasing from 6.6% in 2020 to 13.1% in 2030 and 18.7% in 2050 (What does net-zero emissions by 2050 mean for bioenergy and land use?, 2021). The IPCC (Intergovernmental Panel on Climate Change) believes that bioenergy has a significant climate change mitigation potential if implemented correctly. Most of the IPCC's pathways including substantial contributions from bioenergy in 2050 (average at 200 EJ) (IPCC, 2019).

2.1 Biomass in Nepalese Context

The energy consumption by fuel type in three consecutive years is shown in Figure. It shows the dominance of traditional biomass in overall consumption in all years. The increased share of traditional biomass in 2020 is due to a decrease in other commercial energy consumption as a result of reduced economic activities in the year.

The sectoral energy consumption has changed over the last decade. Residential sector consumption decreased from 89% in 2009 to 63% in 2021 due mainly to the growth in economic activities, use of modern technologies, and energy efficiency improvement. Industry sector consumption has increased significantly to 18% followed by the commercial sector (7%), transport (9%) agriculture (1.6%), and construction and mining (0.8%) in 2021. The effect of growing economic activities is seen mainly in– the industrial, commercial, transport, and agriculture sector. (Nepal Energy Sector

Synopsis Report , 2022).But the biomass comprises of 63% of total energy and 80% of the rural energy. So, Biomass plays an important role in energy context in Nepal. So, it is important to upgrade the raw biomass into more compact form like pellets(wood) or by different conversion process. The conversion of raw biomass leads to reduced transport cost as it transports more dense energy comparison to the traditional one. This leads to higher energy content per weight of the fuel and reduce the pollutants. Traditional biomass can be converted to modern system of biomass.

2.2 Improved Cooking Stoves

A rocket stove is a type of Improved Cooking Stove (ICS). It is an efficient cooking stove using small diameter wood fuel which is burned in a simple high-temperature combustion chamber containing an insulated vertical elbow which ensures complete combustion prior to the flames reaching the cooking surface.

A rocket stove achieves efficient combustion of the fuel at a high temperature by ensuring a good air draft into the fire, controlled use of fuel, complete combustion of volatiles, and efficient use of the resultant heat. It has been used for cooking purposes in many energies' poor locals as well as for space and water heating. (Alternative Energy Promotion Centre, n.d.).

Nepal has a total of 5.4 million households, 74.4% of which use solid biomass such as firewood and dung for cooking. Around 1.78 million households use some kind of clean cooking energy. Out of the total households, 2.4% use biogas 0.1% use Kerosene, 21% use LPG, 0.1 % use electricity, and 8.3% use Improved Cooking Stoves (ICS). Eighty three percent of the total population of Nepal lives in rural areas and most of them do not have access to clean cooking energy. They use firewood and cattle dung on a traditional three stone or metal tripod stove. Approximately 3 million households qualify only for ICS in the short term and some 800,000 households qualify for domestic biogas, particularly those currently using cattle dung for cooking. (Nepal Beuerue of statstics, 2020)

ICS is a simple cooking energy technology with significant socio-economic and environmental benefits with the potential of reaching millions of rural poor of low level of the energy ladder in Nepal. There is an urgent need and considerable opportunity for higher and more pervasive installation rates, particularly targeting the poor regions of Nepal, that have benefited little from the national programme, but following a market led and sustainable approach.

2.3 Different Parameters of Improved Cooking Stove

Improved stoves come in various sizes and types. The dimensions can vary depending on the intended use, such as portable camping stoves or larger, stationary models for household cooking.

AAnthony A. Bantu et.al has conducted a test on Improved cooking stoves that showed the 78.8% more reduction over the baseline open fire stove. (AAnthony A. Bantu, 2018).

Nathan G. Johnson and Kenneth M. Bryden identifies different factors like cookstove application, family size, total mass of wet and dry ingredients, mass of dry ingredients, the use of burning embers as an igniter, and the number of fires used during a cooking even for fuel consumption. In addition, the type of cookstove had limited impact on fuel consumption (Bryden, 2012).

Patinkin evaluated the energy and energy efficiency of grass, vegetable oil, manure, treated and untreated wood, straw, sludge and Charcoal as biofuel. The energy efficiency was calculated using the lower heating value and exergy efficiency was tested for chemical exergy alone and combined chemical and physical exergy. Wood is a preferable and superior solid fuel, but when wood is not accessible other biomass fuels can be used. (Mohammadreza Sedighia, 2017)

Arora et al. reported that different fuel types produce different ranges of CO and PM emissions. Mustard stalks increased the CO to 45% and PM to 70% over firewood and kerosene, respectively. They studied the effect of fuel feeding interval on CO emissions. A fuel feeding interval of 15 min increased the CO concentrations up to 60% over a fuel feeding interval of 7 min as a result of smoldering (Mohammadreza Sedighia, 2017).

Okonkwo, Ugochukwu C et.al developed a rocket stove using wood ash gotten from teak (khaya grandiflora) as insulator, the test has shown that the construction of a rocket stove using wood ash as insulator perform better and more efficient. (Okonkwo, 2017).

Aayush Parajuli and et.al conducted a numerical analysis on stove with five different material and found that the one with less conductivity is efficient for cookstove and with high conductivity is efficient for space heating. (Ayush Parajuli, 2019).

All the research conducted are to increase the efficiency of the cook stove. Generally, efficiency rating is dependent upon fuel type, fuel feed and various other factors.

Chaya Chengappa found the reductions of PM2.5 during the other seasons, however, indicated that the Sukhad stove resulted in approximately 40 % reduction in 48-hour average kitchen concentrations. The Sukhad stove also resulted in approximately 30 %

reduction in 48-hour average CO kitchen concentrations. Although during the summer the reported reductions were greater (69 %), the sample size was much smaller; the average concentration of CO was 50 % lower than that observed during the other two seasons. Possibly the reduced use of cow dung during the summer resulted in decreased CO concentrations, given that the overall combustion in the stove would be improved (Chaya Chengappa, 2007).

The thermal efficiency is a comprehensive measure of how well the stove converts the chemical energy in the fuel into useful heat. It takes into account both the combustion efficiency and the heat transfer efficiency.

Lawal, S recommends that the modifications made in providing insulation around the combustion chamber and sizable air inlet to admit adequate quantity of air for combustion, incorporating smoke rings to seal the annulus between the pot and pot-hole, and redesigning the configuration of the pot seat and the position of the gas exit port, have served to increase the thermal efficiency and therefore the percentage heart utilization of the stove. (Lawal, 2023).

The result revealed that the rocket stove has 29% thermal efficiency, 43% reduction in specific fuel consumption, 42% CO and 81% PM2.5 emission reduction as compared to the well-known utilized traditional three-stone stove in Ethiopia. The experiment revealed that, the rocket stove average emission is 1.8 µg/m3 CO and 10 µg/m3 PM2.5 respectively. The emissions characteristic of their stove satisfies the WHO indoor air quality standard. (Mekonnen, 2019)

It is also clear that larger the pot size and heat transfer area, the better is the heat transfer, and this shows a saturating trend with further increase in heat transfer area. (Kailashnath Satur, 2015)

The laboratory measurements on cookstoves show a lot of scatters in data indicating very high uncertainty which can, at times, smear out the trends in the data. (Kailashnath Satur, 2015)

There are conflicting reports on relationship between efficiency of a cookstove and the fire power: some indicating near invariance of efficiency with increase in power, some giving decrease of efficiency with increase in power, some giving opposite trends, some showing a range of power with maximum efficiency and a few others giving no trend at all. An in depth understanding of the processes in a cookstove supports the characteristic of efficiency versus power having an inverted bowl shape over a wide range of fire powers. Thus, depending upon the range of power over which the cookstove is tested, one may get any of the trends indicated above. If the data has very high uncertainty, no clear trends will emerge from the data. (Kailashnath Satur, 2015).

2.4 Force Draft and Natural Draft Stoves

Chaurasia found out that the force draft rocket stoves are 12-15% more efficient than normal improved stoves and 8-10% efficient than Natural Draft stoves . (Chaurasia, 2018).

Nordica, Dean, & Damon found out that force draft stove reduces energy use by 40% and emission by 90% compared to traditional stove while natural draft rocket stove can reduce energy use by 33% and emission by 75%. (Nordica, Dean, & Damon, 2010).

Bentson, Evitt, Still, Liberman, & MacCarty, 2022 found out that Jet-Flame significantly improved stoves when carefully tended with a single layer of sticks. On a global average, it led to an 89% reduction in PM2.5 compared to natural draft cases, showing greater enhancements in most stove types. Additionally, CO levels decreased by 74% on average, achieving tier 4 or 5 ratings for all stoves. Thermal efficiency also saw a boost, with a 34% increase when not considering the energy content of the remaining char, or a 21% increase when considering char. (Bentson, Evitt, Still, Liberman, & MacCarty, 2022)

2.5 Fuel Type and Avaibility

Generally, firewood is easily available while charcoal and wood pellet goes through pyrolysis and pelletizing respectively.

Nordica, Dean, & Damon found out that a rocket-type charcoal stove can reduce this energy consumption by one third and CO emission by at least one half. (Nordica, Dean, & Damon, 2010).

Wyatt & P.Grieshop, 2019 analyzed that pellet stoves have the potential to provide health benefits far above previously tested biomass stoves and approaching modern fuel stoves like LPG.It is also observed that the emission reduced by more than 90% (Wyatt & P.Grieshop, 2019).

2.6 Marginal Abatement Cost

Marginal abatement cost" is a term commonly used in the context of environmental economics and climate change mitigation. It refers to the cost associated with reducing or "abating" one additional unit of pollution or greenhouse gas emissions.

Hari Bahadur Darlami et.al found that Marginal abatement cost of best dimension cookstove has been found minimum NPR 445/tCO_2eq and maximum for the cookstove with the use all the accessories NPR 600/ tCO_2eq. (Hari Bahadur Darlami, 2020).

Young-Hwan Ahn and Woo young Jeon study derived the MACCs in the Korean power sector in 2030 for the three scenarios based on different carbon pricing schedules. In addition, they investigated how much carbon price is needed to meet the 2030 mitigation target in the sector using the MACCs and what the generation mixes are. It was found that the linear scenario induces more reductions than the one-point scenario with the same carbon price. (Jeon, 2019).

Year	Title	Author	Study	Research Gap
2023	Comparative Studies of Single and Cascaded Rocket Firewood Burning Stoves Based on Energy Analysis Method	Lawal, S. Abubakar, H. N., & Mati, A. A.	Modifications made in providing insulation around the combustion chamber and sizable air inlet to admit adequate quantity of air for combustion, incorporating smoke rings to seal the annulus between the pot and pot-hole, and redesigning the configuration of the pot seat and the position of the gas exit port, have served to increase the thermal efficiency and therefore the percentage heart utilization of the stove	
2020	Design and performance analysis of institutional cooking stove for high hill rural community of Nepal	Prabidhi Adhikari, Aashish Adhikari, Shree Krishna Dhital, Bijendra Shrestha, and Hari Bahadur Dura	The stove thus manufacture had 31% thermal efficiency. The stove emission was measured for PM2.5 and CO with average value of 109 µg/m3 and 3.6 ppm respectively. Thus, the result shows that the stove is efficient in ways, fuel efficiency and emission criterion.	

Year	Title	Author	Study	Research Gap
2020	Socio-Economic Analysis of Two Pot Raised Mud Improved Cookstove in the context of Nepal	Hari Bahadur Darlami, Suvita Jha and Bishnu Kumari Budha	Benefit cost analysis and Net Benefit including Environmental benefits has been studied	Economic Analysis of Improved Cookstove stove can be performed for commercially available stoves.
2019	Design and Performance Evaluation of Rocket Stove for Cleaner Cooking in Rural Ethiopia	Bassazin Ayalew Mekonnen	The result revealed that the rocket stove has 29% thermal efficiency, 43% reduction in specific fuel consumption, 42% CO and 81% PM2.5 emission reduction as compared to the well-known utilized traditional three-stone stove in Ethiopia. The experiment revealed that, the rocket stove average emission is 1.8 μg/m3 CO and 10 μg/m3 PM2.5 respectively. The emissions characteristic of our stove satisfies the WHO indoor air quality standard.	No comparison with other similar efficient different fuel cooked stove. No benefit-cost ratio was calculated
2019	A simplified model for understanding the performance of two-pot enclosed mud cookstoves	Ayush Parajuli, Saurabh Agrawal, Janak Kumar Tharu, Anil Kumar Kamat, Ajay Kumar Jha and	They conducted a numerical analysis on stove with five different material and found that the one with less conductivity is efficient for cookstove and with high	Efficiency Parameters can be compared for different materials and insulation for commercially available cookstoves.

Year	Title	Author	Study	Research Gap
		Hari Bahadur Darlami	conductivity is efficient for space heating	
2019	Power sector reform and CO_2 abatement costs in Korea	Young-Hwan Ahn, Wooyoung Jeon	study derived the MACCs in the Korean power sector in 2030 for the three scenarios based on different carbon pricing schedules. In addition, they investigated how much carbon price is needed to meet the 2030 mitigation target in the sector using the MACCs and what the generation mixes are.	
2018	Design of Improved Cookstove Using High Density Heated Rocks and Heat Retaining Techniques	Aanthony A Bantu, Gilbert Nuwagaba and et.al	There is reduction in 78.8% Fuel over Baseline Open Fire	No comparison with other similar efficient different fuel cookstove.
2016	Performance Assessment and Analysis for Potential Promotion of Improved Cookstoves in Nepal under Market/Non-Market Mechanism.	Umesh Sharma and Hari Bahadur Darlami	The Research focuses on thermal efficiency, emission and use of rocket stove in different region.	Emission reduction calculation and associated financial analysis can be done for the scenario of promotion of biogas, LPG and electricity as clean cooking technologies.

CHAPTER THREE: RESEARCH METHODOLOGY

This research aims to focus on Comparative Analysis of Different Type of Improved Cooking Stove in Nepalese Market. The Comparative Analysis is based upon Different Parameter i.e., Technical Parameters, Emission Parameters, Efficiency Parameters and Environmental Parameters. The Overall Research is mainly divided into Four Phases: Initially the literature review was conducted for finding out the Research Gaps and Important Parameters regarding the Analysis of ICS. After Conducting the literature review, Experimental data are collected from RETS. The Experimental Data are obtained from Water Boiling Test (WBT) in a laboratory conditions. The Water Boiling Test Simulates the cooking techniques in a laboratory conditions. The data thus obtained are compared on the basis of different parameters and results are drawn from it. The results thus obtained will be more analytical and the best performing will be subjected to Experiment. Comparative analyses were conducted to ascertain the stove's efficiency, suitability, and environmental impact with each fuel type. The culmination of the analyses provided insights into the optimal fuel type for the identified best-performing stove within the Nepalese market context.

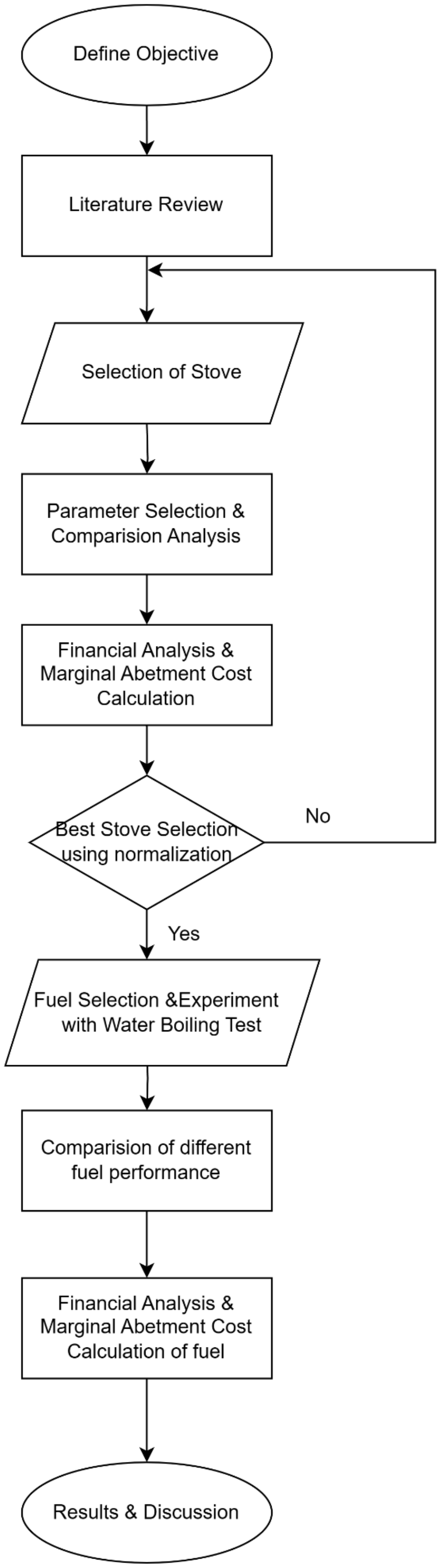

Figure 3.1 Flowchart of Methodology

3.1 Literature Review

From the literature review performance of improved cooking Stove depends upon various parameters. Like Technical Parameters, Efficiency Parameters, Cost Parameters, Emission Parameters and Environmental Parameters. This study mainly focuses on comparative analysis between different ICS on various parameters. The result obtained by various analysis will be compared between various factors for the most effective cooking stoves available in Nepal.

3.2 Data Collection

Data for the experiment were gathered from multiple sources, relying on the Renewable Energy Testing Service (RETS) and experimental data. The collected data included information regarding the efficiency, heat output, fuel consumption, and emissions of the selected cooking stoves.

3.2.1 Improved Cooking Stove Selection

Five Stoves were selected for the study. The description of the stoves are as follows

Table 3.1 Parameters of Different Improved Cooking Stoves

S.N.	ICS Code	Description	Burn Tube	External Diameter
1.	ICS 1	Charcoal and Natural Draft Stove	ϕ10cm×16 cm	ϕ 16cm×10 cm
2.	ICS 2	Wood Pellet and Force Draft	ϕ 9.7cm×19.5cm	ϕ 20cm×36.7cm
3.	ICS 3	Wood Fire and Natural Draft	ϕ 10.5cm×20 cm	ϕ 25cm×31cm
4.	ICS 4	Wood Fire	ϕ 17.5cm×17 cm	ϕ 21.5cm×37.5cm
5.	ICS 5	Wood Fire	ϕ 8.5cm×17 cm	ϕ 26.3cm×25.8cm

The study focused on selecting five distinct ICS for comprehensive analysis. The choice of these stoves was based on two primary factors: efficiency and availability within the context of the Nepalese market. To ensure a representative sample, stoves were selected from various manufacturers and designs, considering their performance metrics and their accessibility in the local market. The selection aimed to cover a spectrum of efficiency levels and design variations commonly found in Nepalese households.

The analyses of selected cooking stoves were conducted to evaluate the stoves based on these performance indicators, allowing for a preliminary identification of the most promising stove among the selected sample.

The collected data underwent through analysis to identify the stove demonstrating superior performance across the specified criteria. Criteria such as efficiency, heat output, fuel consumption, and emissions were scrutinized to determine the stove with the most favorable attributes for further experimentation. The stove identified as the best performer within the Nepalese context based on the initial analysis was chosen for subsequent experimental validation.

3.2.2 Normalization

The secondary data thus analysis through different parameters was transformed to a standardized within a range making them comparable. So, Normalization technique was used for choosing the best stove among them. The scale is from Zero to one.

$$Normalized\ Value = \frac{C_i - C_{min}}{C_{max} - C_{min}} \quad 3.1$$

Where,

$$C_i = Value\ of\ the\ ICS$$
$$C_{min} = Minimum\ Value\ among\ ICS$$
$$C_{max} = Maximum\ Value\ among$$

This shows that the higher the value, the better is the ICS.But for emission, fuel consumption and cost, the lower the value, the better is the ICS.So, they are transformed into same scale for the comparison.

$$Transformed\ Value = 1 - Normalized\ Value \quad 3.2$$

The Transformed Value are then weighted average and then compared for the same scale.

3.2.3 Fuel Selection

The selected stove was tested using three different fuels i.e., Firewood, Charcoal and Wood Pellet with Net Calorific Value (NCV) 20MJ/kg,20MJ/kg and 29 MJ/kg respectively with charcoal and wood pellet moisture contain about 10% and firewood about 13%. The selected fuels are used in water boiling test.

3.3 Experimental Setup

The selected best-performing stove was subjected to experimental testing under controlled conditions. The experimental setup aimed to evaluate the stove's performance with different fuels, including locally available biomass sources commonly used in Nepalese households. Measurements were taken for efficiency, heat output, and fuel consumption to assess the stove's adaptability and effectiveness with various fuel types.

3.3.1 Water Boiling Test

Performance test of the ICS was evaluated by Water boiling Test (WBT), version 4.2.3.

The experimental set was set according to the protocol. For each set of tests, a 7-liter pot was weighed and filled with 5 kg of water. Fuel was pre-weighed along with the kindling. Ambient and initial water temperature was measured. The char container's initial weight was also noted. The stove was filled with fuel, and a fire was started with some amount of kerosene as fire-starting material. The stopwatch was started to measure the time duration of testing. After the water reached a rolling boil, the water temperature was noted. The weight of unburned fuel left the char, and the water were also noted. The first test was started at room temperature, and hence, it is the cold start phase. The procedure for the hot start phase is the same as above. For Simmering phase, the water from the above phase is weighed and the fuel is fed on the stove, when fire was caught the stopwatch was started. The water temperature is maintained at 3 degrees Celsius below the local boiling temperature and final temperature and pot was weighed with remaining water. This is low power phase or simmering phase. The process is repeated three times for one fuel.

3.4 Calculation and Data Presentation

After the performance test evaluation by Water boiling test 4.2.3 spreadsheet was used to calculate the different parameter i.e., firepower, burning rate, turn down ratio and thermal efficiency.

3.5 Data Analysis

The data obtained from experiment are compared for different fuel. Thus, obtain parameters were compared with lab tested data obtained with the experimental data are compared.

3.5.1 Emission Reduction Calculation

Emission reduction is calculated using the formula suggest by AMS II. G/V06 methodology (UNDP, 2016)

$$ER_{yi}, = B_{y\,savings} \times N_{y,i,a} \times \mu_{yi}, \times 365 \times f_{NRB,y} \times NCV_{NRB} \times EF_{projectedfossilfuel} - LE_y \quad 3.3$$

Where,

$B_{y\,savings,i,a}$ =Quantity of woody biomass saved in tons per cook stove device of type i and age in year y.

$N_{y,i,a}$ =Number of project devices of type i and age operating in year.
μ_{yi} = Number of days of utilization of the project device during the year 'y'.
$f_{NRB,y}$ =Fraction of woody biomass saved by the project activity in year y that can be established as non-renewable biomass using survey methods or government data or default country specific fraction of non-renewable woody biomass (f_{NRB}) values available on CDM website.
NCV_{NRB} =Net calorific value of the non-renewable woody biomass that is substituted.
$EF_{projectedfossilfuel}$=Emission factor for the substitution of non-renewable woody biomass by similar consumers (81.6-ton CO2/ TJ).
LE_y= Leakage emissions in year y.

3.6 Financial Analysis

The financial analysis of the stove was performed on the basis of life span, fuel and its maintenance cost. The total cost was calculated as per lifetime of the stove and following analysis was performed.

3.6.1 Discounted Payback Period

It is calculated by discounting the cash flows that are to be generated in future and then totaling the present value of future cash flows where discounting is done by the weighted average cost of capital or internal rate of return. (Park, 2013)

Discounted Payback Period = Year Before the Discounted Payback Period Occurs + (Cumulative Cash Flow in Year Before Recovery / Discounted Cash Flow in Year After Recovery)

3.6.2 Net Present Value (NPV)

The net present value (NPV) is the difference between the present value of the cash flows PVCF (the benefit) and the cost of the investment (IO): NPV = PVCF – IO. (Park, 2013)

$$NPV = \frac{R_t}{(1+i)t} \qquad 3.4$$

Where,
t= time of cash flow
i=discount rate
$R_t = net\ cash\ flow$

3.6.3 Internal Rate of Return

The internal rate of return (IRR) formula is based on the net present value (NPV) formula when it's used to solve for zero NPV. (Park, 2013)

The internal rate of return formula is:

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} - C_0 = 0 \qquad 3.5$$

Where,

$C_t = Net\ Cash\ Flow\ during\ Period\ t$
$C_0 = Total\ Initial\ Investment\ Cost$
$IRR = Internal\ Rate\ of\ Return$
$t = Number\ of\ time\ Periods$

3.6.4 Risk Analysis

The risk analysis was performed by Monte-Carlo Simulation. In this analysis, the assumption was made as Fuel use, Operation and Maintenance cost, Cost of the fuel for ICS and TCS and discount rate was also considered assumptions. The NPV was taken for forecast.

Cost and discount rate was considered as Normal distribution considering the data to be clustered around the mean value. Operation and Maintenance cost was considered as Triangular distribution as there is limited data available from the manufacturer as it has more extreme value rather than exact value. Fuel cost was considered lognormal value as it is skewed and value cannot be negative as fuel cost cannot be negative.

After assigning distribution, random samples were generated through Monte-Carlo simulation and calculations were performed for probability or certainty of NPV.The results were aggregated and analyzed for risk calculation of the NPV.

3.6.5 Benefit Cost Analysis (B-C Ratio)

Calculate the present value of the benefit expected from the project. The procedure to determine the present value is given by (Park, 2013)

The amount for each year = Cash Inflows*PV factor

Aggregate the amounts for all the years.

Calculate the present value of costs. If the costs are incurred upfront, the cost incurred is the present value

of the expenses as there is no PV factor.

Calculate the benefit-cost ratio using the formula:

$$Benifit\ Cost\ Ratio = \frac{\sum Present\ Value\ of\ Future\ Benifits}{\sum Present\ Value\ of\ Future\ Costs} \qquad 3.6$$

3.7 Marginal Abetment cost

The marginal abetment cost is calculated as

MAC = (Total Cost of Mitigation Option B - Total Cost of Mitigation Option A) / (Reduction in Emissions from Option A to Option B).

It is also written as

$$MAC = \frac{Cost\ of\ abetment}{Quantity\ of\ abetment} \qquad 3.7$$

CHAPTER FOUR: RESULTS AND DISCUSSION

The different parameters are compared with each other for five different types of ICS. The combination of all the factors will be consider for recommendation of the stoves. Different factors such as emission, financial analysis, turn down ratio, etc. was considered for the comparison of different type of ICS. The best in terms of every parameter will be taken and a Natural and a Force Draft stove that has diverse and the best among comparison will be considered.

4.1 Comparative Analysis

4.1.1 Firepower

Firepower is the fuel energy consumed to boil the water divided by the time to boil. It tells the average power output of the stove during the high-power test. The Firepower of different ICS has been shown in Figure 4.1

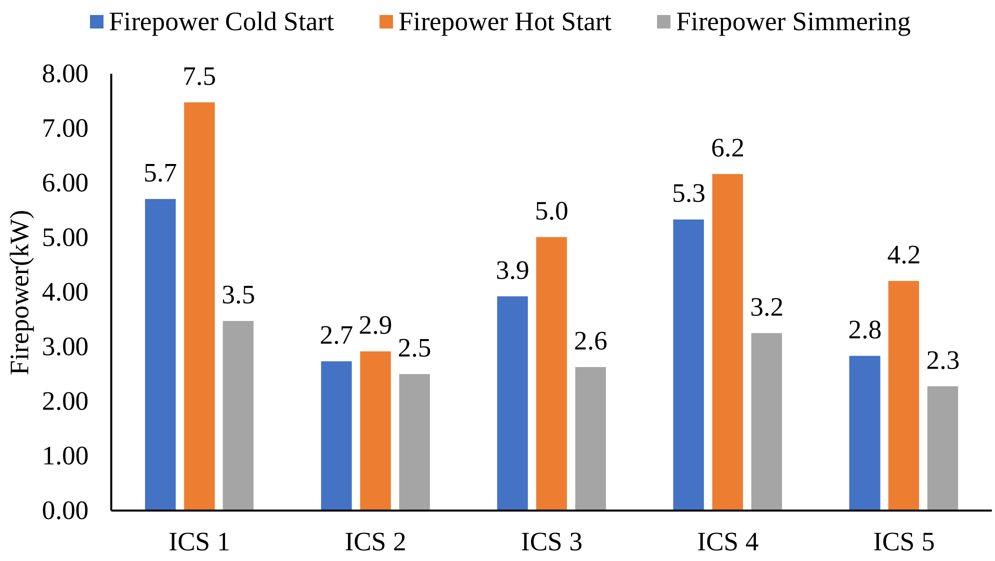

Figure 4.1 Comparison of Firepower of different ICS

From the above chart it was shown that ICS 2 consume less fuel to boil per time of the water in average for all three starts. The ICS 1 has the highest Firepower for Cold and Hot start with 5707.1 W and 7094 W respectively. The lowest being ICS 2 for Cold and Hot Start 2735.16W and 2918.47W respectively. The ICS 5 has the least Simmering Firepower with 2275 W.

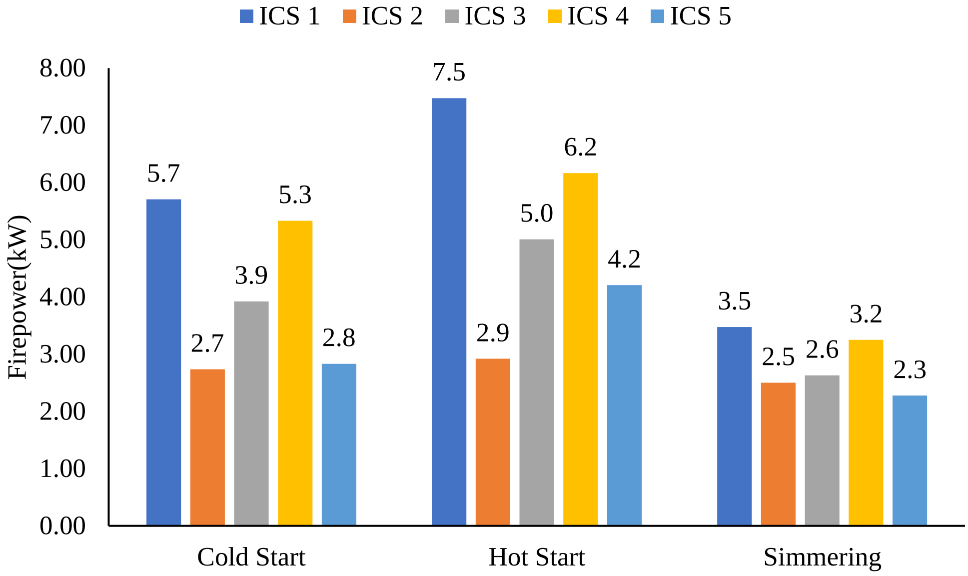

Figure 4.2 Comparison of Firepower of different ICS at different phase

The above Figure 4.2 shows the Firepower at different start. The firepower generally depends upon size. It is clear that ICS 1 has larger size compared to other. More energy is required for cold and hot start compared to that of simmering. The above compassion shows that the firepower for simmering is very lower compared to that of cold and hot start. Generally, firepower is the not the prominent factor to determine the simmering phase. The general trend shows the simmering requires less firepower compared to the high-power test. From the figure above, it is known that ICS 2 has the least simmering power.

The average firepower of average high-power firepower is the mean of Cold start firepower and hot start firepower. The firepower generally illustrates heat power of the stoves and how fast the fuel is burning. The average high-power firepower is shown in Figure 4.3.

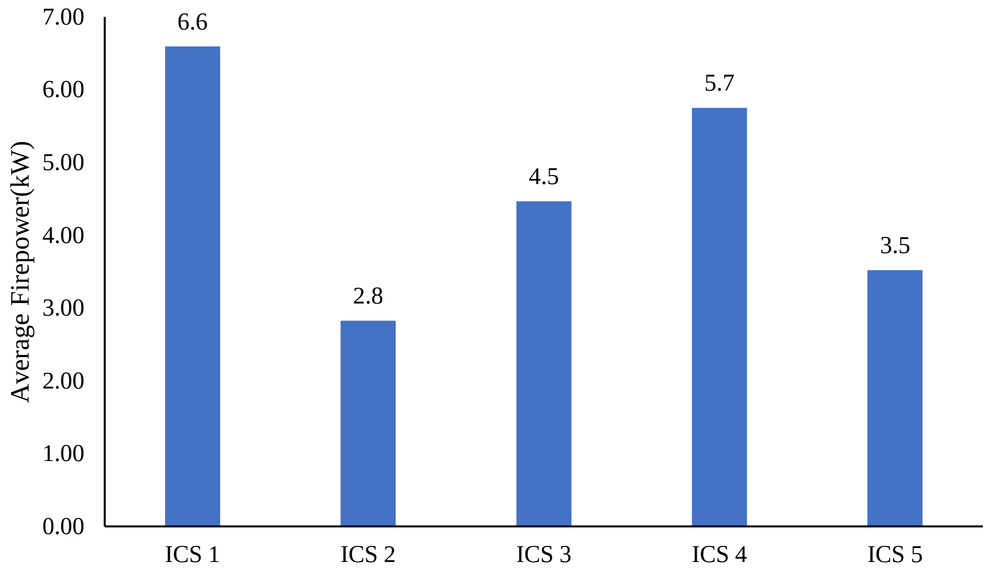

Figure 4.3 Average High Firepower of Different Stoves

The average high firepower was compared to each other. Firepower provides the better scenario of output power in the stove. More Firepower is required for cook boiling. So, it is seen that ICS 1 has the high Firepower. It means it takes less time to boil.ICS 2 has the lowest firepower, so the boiling time is high.

4.1.2 Time to Boil

The Scatter diagram between Firepower and Time to boil for cold start has been shown in the Figure 4.4.

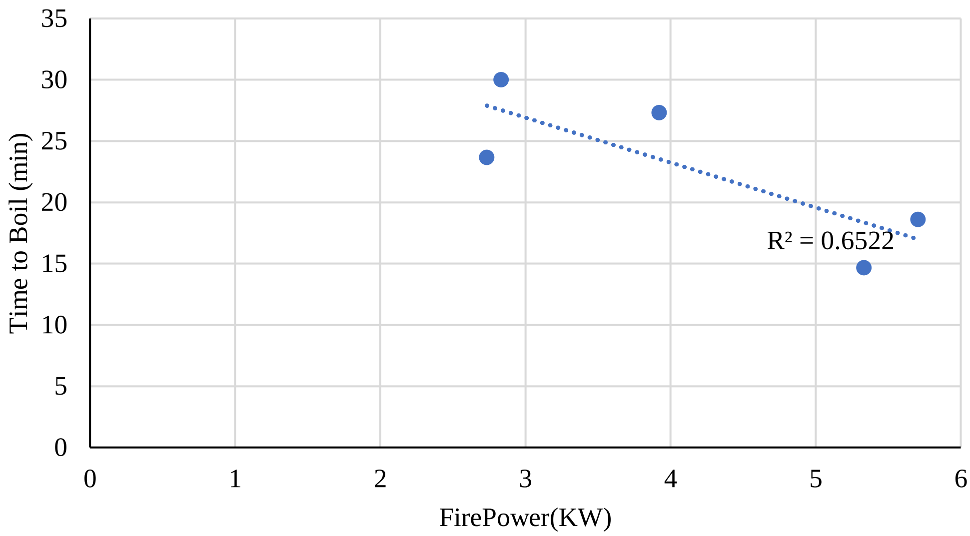

Figure 4.4 Firepower vs Time to Boil (Cold Start)

From the above Firepower vs Time to boil at cold start shows that time to boil is quiet dependent on Firepower. They both have linear regression line and are negatively correlated i.e. When the Firepower decreases, time to boil increases and vice versa. It has a R^2 Value of 0. 6522.The result shows that the time to boil for cold start depends upon different other factors too. The Scatter diagram for the hot start is plotted and shown in the Figure 4.5

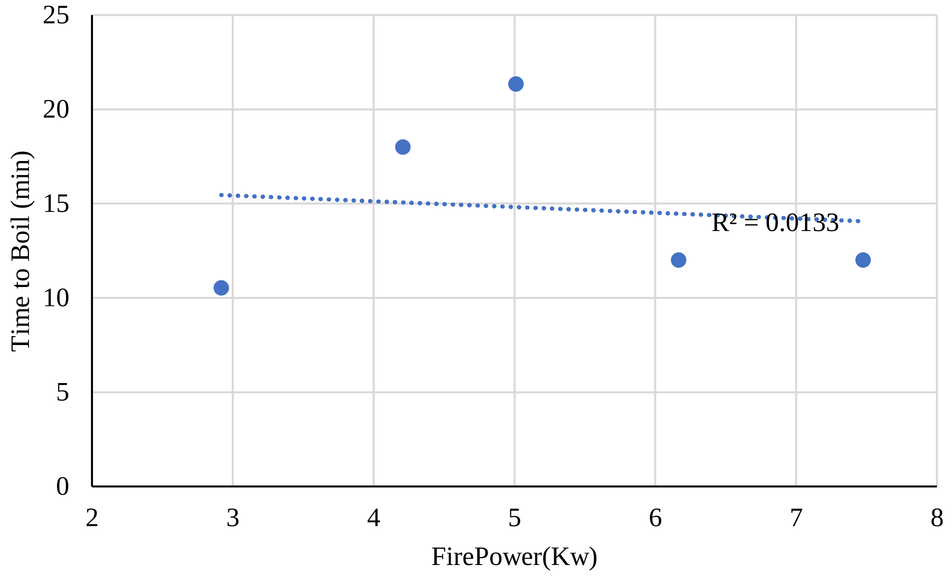

Figure 4.5 Firepower vs Time to Boil Hot Start

From the above figure, the time to boil is unlikely to depend upon Firepower. They have a very low R^2 value is 0. 0139.The negative corelated model unlikely to depend upon each other. For the hot start, time to boil is independent upon the firepower.

The Time to boil for cold and hot start is illustrate in Figure 4.6

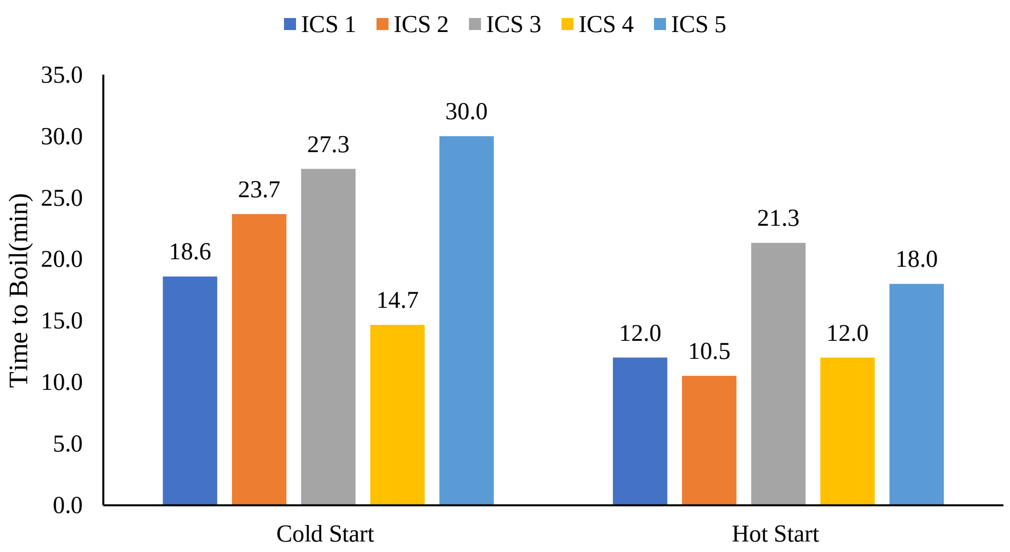

Figure 4.6 Time to Boil

This shows that time to boil is higher in case of cold start. The cold start starts at ambient temperature and hence require more time to boil the water. But at the hot start, the vessel is already heated and hence requires less time to boil. From the above illustration it is clear that, at cold start ICS 4 takes less time to boil while ICS 5 takes most time to boil.ICS 3 takes the longest time to boil at hot start while ICS 2 takes least time to boil at hot start. There is no boiling of water during the simmering of water.

The Scatter plot of Firepower and Energy to cook is shown in Figure 4.7

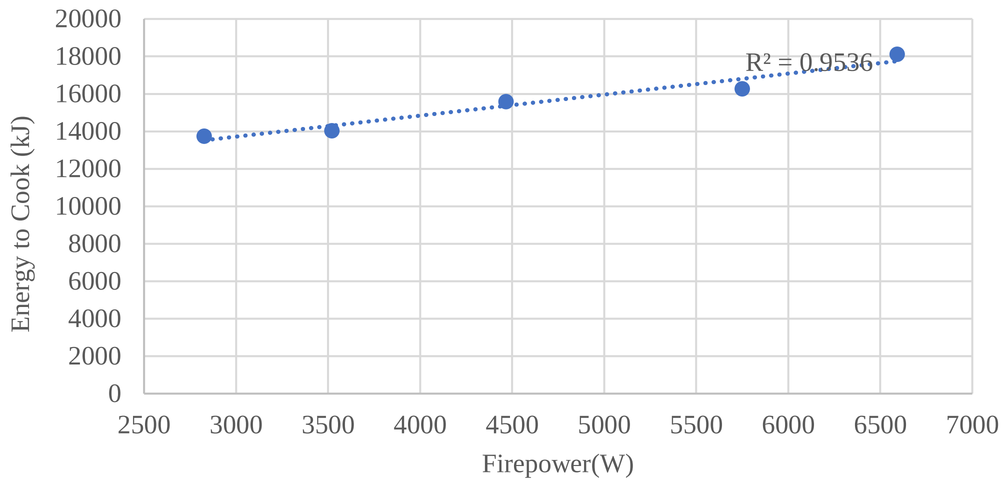

Figure 4.7 Firepower and Energy to Cook

Energy to cook is high for high firepower in general but with ICS 5, the firepower is very less compared with others but the energy requires to cook is on higher side compared to other. The Firepower and Energy to cook shows the uptrend with R^2 =0.9536 which shows a strong correlation between them. The firepower and energy required to cook shows a direct relationship i.e., the more the firepower, the more is the energy used to cook.

4.1.3 Thermal Efficiency

The High-Power test is performed as Cold Start Test and Hot Start Test while low power test is called Simmering test. The thermal efficiency between different stoves is shown in the Figure 4.8

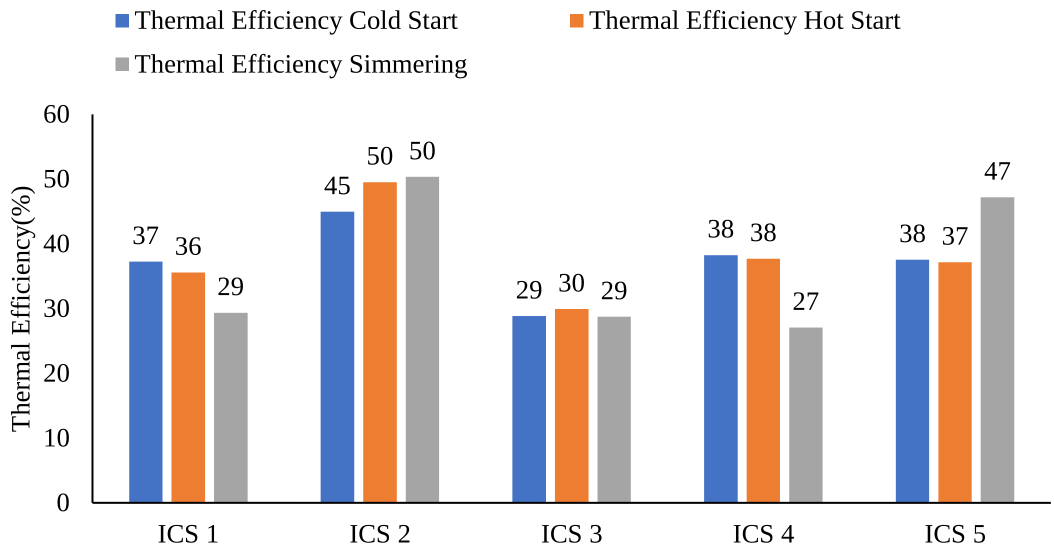

Figure 4.8 Thermal Efficiency of different cookstoves

Generally, the hot start test and cold start test have similar efficiency while Simmering efficiency is inconstant among the test.ICS 2 and ICS 5 have best simmering efficiency and has best high-power efficiency in Force Draft Stove and Natural Draft Stoves respectively.

The cold start efficiency is nearly equal to the average high-power efficiency. The ICS 2 has the highest efficiency of 47.25% while ICS 3 has the lowest with 29.4% efficiency.

ICS 2 has the best simmering efficiency compared to other stoves followed by ICS 5. Simmering efficiency shows the how the heat is converted to the pot during simmering phase. The efficiency at different phases has been illustrate as in the Figure 4.9

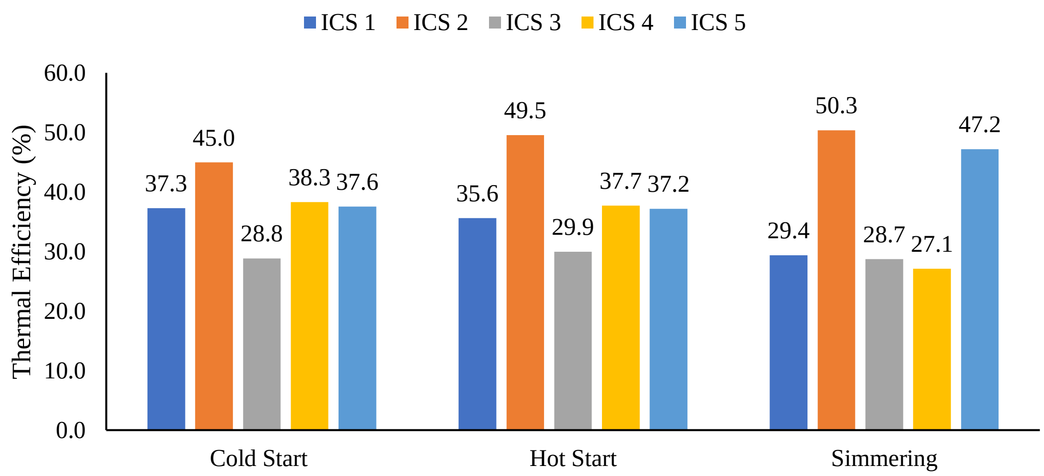

Figure 4.9 Comparison of Efficiency at Different Phase

The above figure illustrate that ICS 2 has the highest cold start, hot start and simmering efficieny.ICS 2 is followed by ICS 4 in cold start. In hot start ICS 2 is followed by ICS 4. The simmering efficiency of ICS 5 is second to ICS 2 while other ICS has very less simmering efficiency.

4.1.4 Turn Down Ratio

The ratio of high and low power is a turn down ratio. The turn down ratio is plotted as shown in Figure 4.10

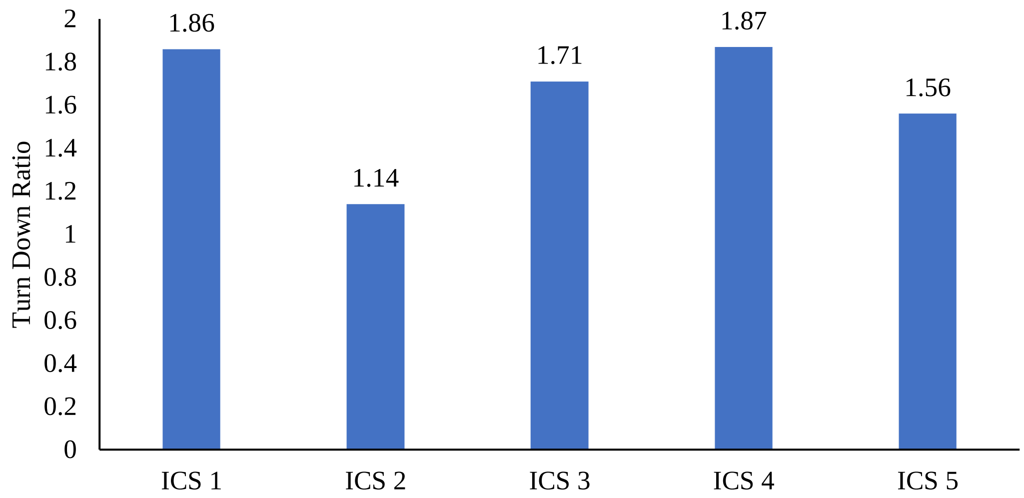

Figure 4.10 Turn Down Ratio of Different stoves

The ratio of the boil and simmer firepower is termed as the turn-down ratio (TDR), which is an indicator of ability of the stove to be “turned down” from boil to simmer phase, and the extent to which stove firepower can be controlled from the above table it is shown that the ICS 4 has the highest turn down ratio while ICS 2 being highly efficient has the lowest turndown ratio. This shows the versatility of ICS 4 compared to that of ICS 2.

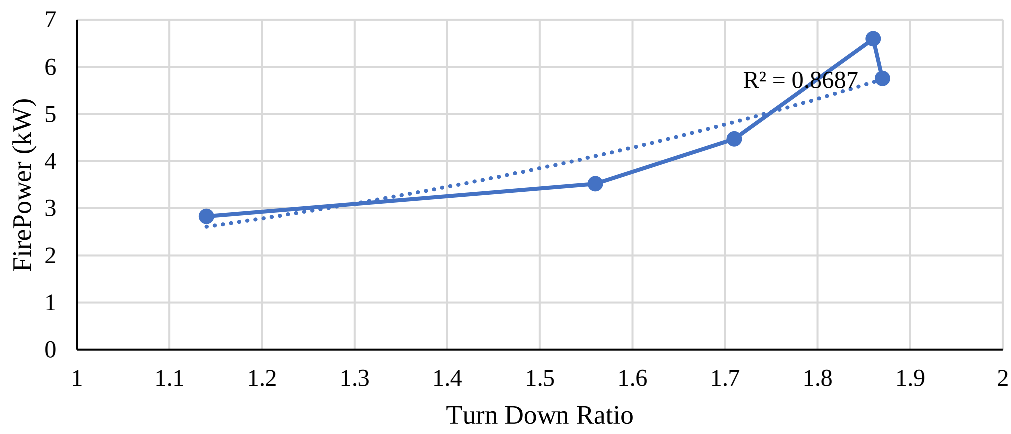

Figure 4.11 Firepower and Turn Down Ratio

The Scatter plot of the Firepower and Turn Down Ratio shows that the R^2 value is 0. 867.The fit is a strong one. It shows that the firepower and turn down ratio are exponentially fit. The turndown ratio and Firepower are exponentially corelated which shows the upward trend. It means the higher the Turn down ratio, the more the Firepower. This shows the correlation with the high-power firepower. As the turn down ratio signifies great high-power firepower compared to low power firepower. Stoves possessing a higher turn-down ratio tend to consume less fuel when used for practical cooking tasks that involve heating food to a boil and subsequently simmering it for an extended duration. This is due to their capability to efficiently adjust and operate at lower heat levels, resulting in reduced fuel consumption throughout the cooking process.

4.1.5 Specific Fuel Consumption

Specific Fuel Consumption determine the amount of fuel consumed during the process. It doesn't imply that higher efficiency has lower fuel consumption or vice versa. The efficiency only take account the fraction of fuel that has reached the pot The Specific fuel consumption of the different type of stoves is shown in Figure 4.12

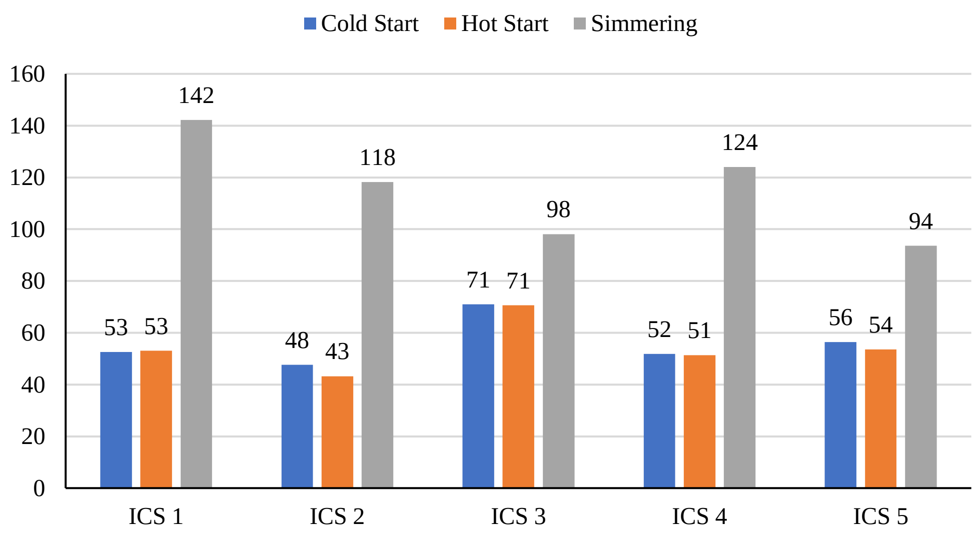

Figure 4.12 Specific Fuel Consumption of Different Stoves

The fuel consumption is least for the ICS 2 while ICS 3 consume high specific fuel at high power phase.

The Specific Fuel Consumption at Different Phases is shown in Figure 4.13.

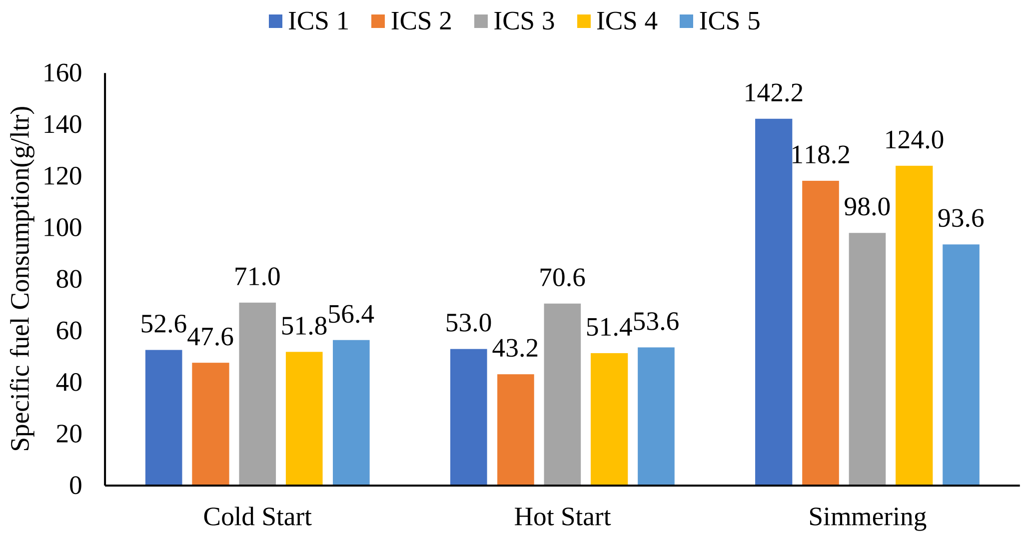

Figure 4.13 Specific Fuel Consumption at Different Phase

The above bar graph shows that the ICS 3 has the most specific fuel consumption and ICS 2 has the least for Cold and Hot start. However, during simmering phase ICS 1 consumed the most amount of fuel. The fuel consumption was high in simmering phase because boiling of water takes place continuously for around 45 minutes at a constant temperature. For ICS 1, in the simmering phase the specific fuel consumption is 142.22 g/ltr.

The specific fuel consumption for simmering for ICS 1 is higher but the efficiency of ICS 2 is high. The specific fuel consumption shows that it has changed with the efficiency. The higher efficient ICS 2 has lower specific fuel consumption while ICS 3 has lower efficiency and higher fuel consumption. The scatter plot for the specific fuel consumption and Thermal efficiency is plotted in the Figure 4.14.

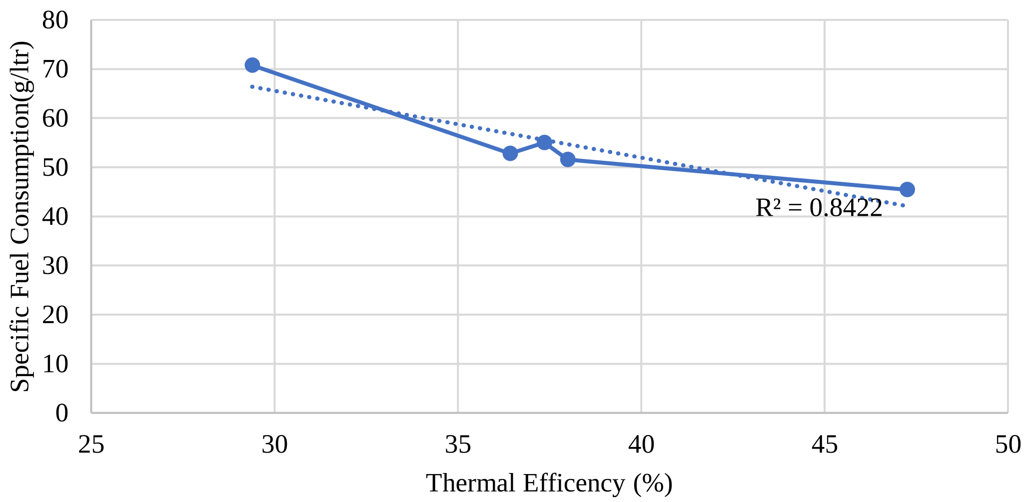

Figure 4.14 Thermal Efficiency vs Specific Fuel Consumption

The figure shows the relation between Thermal Efficiency and Specific Fuel Consumption. The R^2 was 0.84 which shows a strong correlation between efficiency and thermal efficiency. It shows the downward trend. It means that the higher the thermal efficiency, the lower the specific fuel consumption. The statistics is also in accordance to this with confidence interval at 95%.

The fuel consumption per household per year was calculated and is shown in Table 4.1

Table 4.1 Comparisons of Fuel consumption per household per year

Year	Total fuel Consumption per year for different stoves (Metric Tons)					
	TCS	ICS 1	ICS 2	ICS 3	ICS 4	ICS 5
I	3.07	0.84	0.65	1.58	0.81	0.82
II	3.07	0.94	0.72	1.7	0.9	0.91
III	3.07	1.04	0.8	1.83	1.0	1.01

From the above Table 4.1,it is shown that ICS decreases the Fuel Consumption drastically. The Fuel Consumed increase every year as the derating factor for the ICS is assumed 10%. Thus, fuel saving decreases every year. The Fuel Saving on ICS 2 is high and is followed by ICS 4. The efficiency also follows the same trend.

4.1.6 Emission Parameters

During burning of biomass, different gases like Carbon monoxide (CO), Carbon dioxide (CO_2) and PM2.5 etc. are released. This depends upon different various parameters like combustion of fuel, fuel quality, types of fuel and the stove make too.

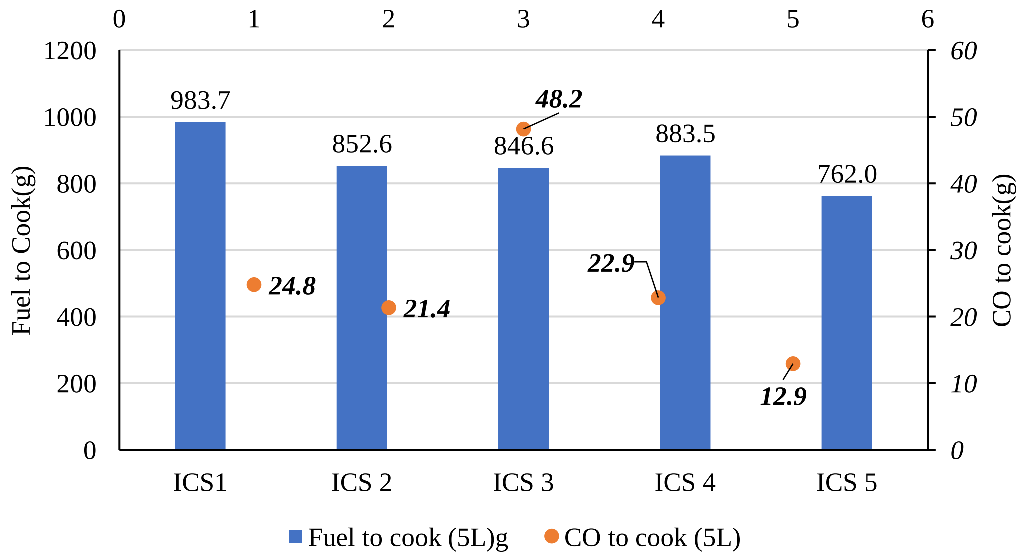

Figure 4.15 Fuel to cook vs CO to cook

From the above Figure 4.15, it shows that the Carbon monoxide is not dependent upon fuel alone but the type of the stove. Generally, Wood Pellet and ICS 4 Wood Fire have less CO compared to ICS 1 and ICS 3 as ICS 2 and ICS 4 are Force Draft Stoves. The force draft stoves produce less carbon monoxide compared to the Natural Draft one.

The CO to cook vs PM to cook shows the similar pattern but the ICS 5 has a different approach. The PM emission is very high for ICS 5.

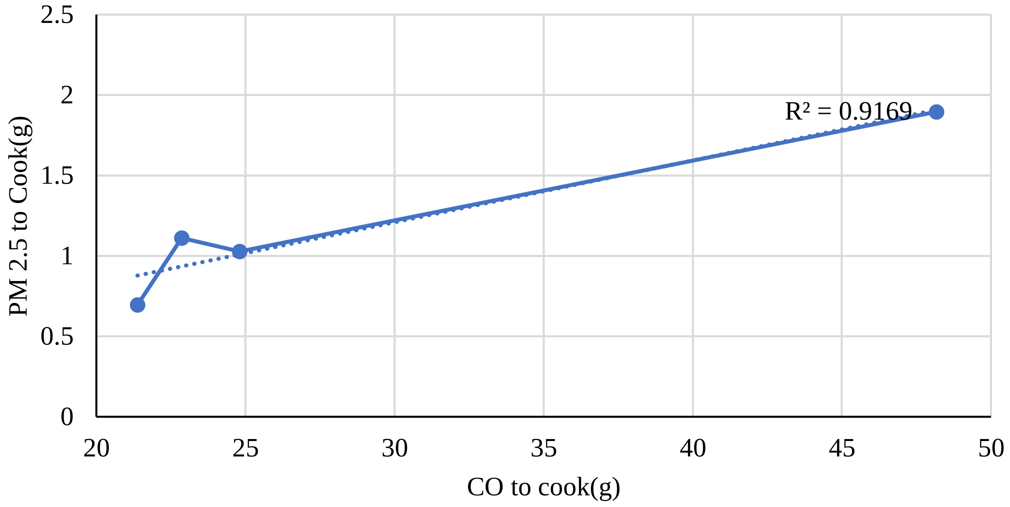

Figure 4.16 PM 2.5 to cook and CO to Cook

It shows that as the CO emission increases the PM2.5 also increase which means that the emission parameter increases as a whole. It Shows a strong up-trend between each other.

The CO to cook required and thermal efficiency are plotted in a scatter plot as shown in Figure 4.17

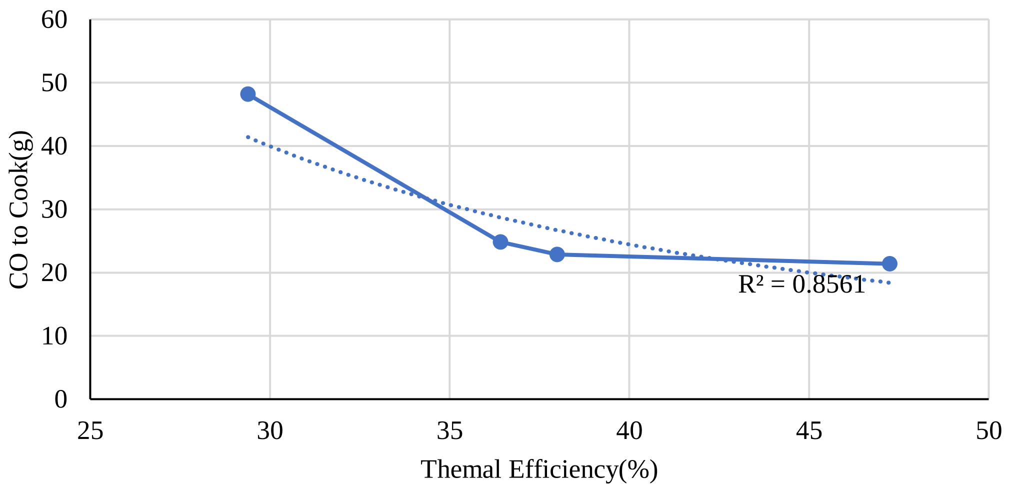

Figure 4.17 Efficiency vs CO to cook(g)

The above scatter plot shows the relationship between efficiency and CO to Cook(g). The R^2 value is 0.856 with downward trend. It means that emission of CO decreases as the efficiency increase that is in line with the principle of the combustion. The higher efficiency, the lower the emission of Carbon monoxide.

The Scatter plot for PM to cook and efficiency are shown in Figure 4.18

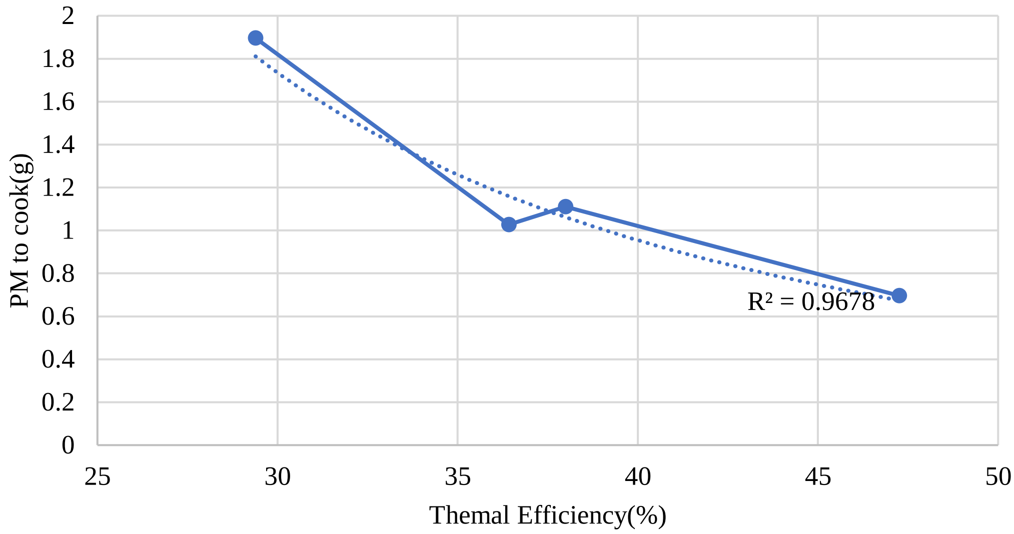

Figure 4.18 Thermal Efficiency and PM to Cook

The above scatter plot shows that it has strong correlation. The PM2.5 decreases with increase in efficiency and vice versa. The above figure shows a downward trend with higher correlation between them. It shows similar pattern as that of CO to cook.

From the above Figure 4.17 and Figure 4.18 shows that the emission decreases with increase in efficiency of the stove.

Now considering all the parameters for Emission i.e., CO to cook and PM2.5 to cook 5 L. The CO_2 is omitted as the results are very incontinent in nature. Comparison between them is shown in Figure 4.19

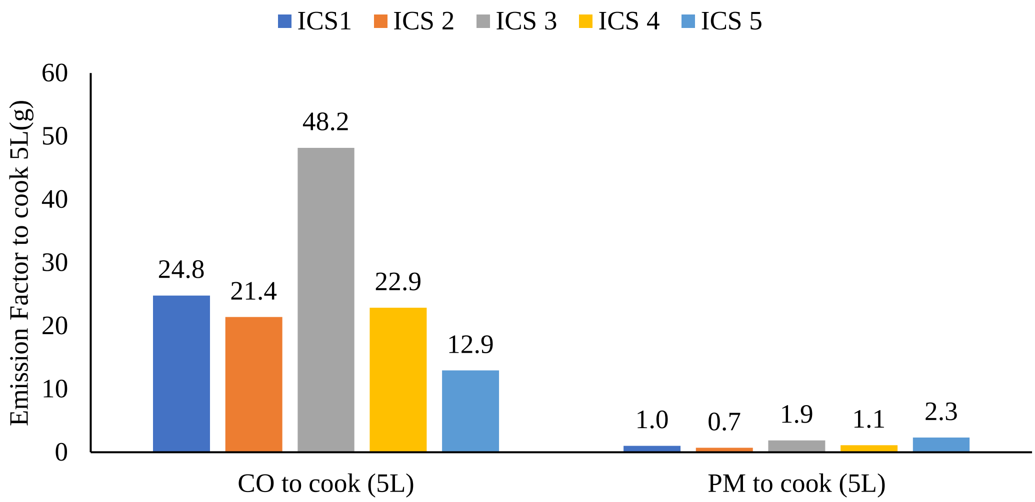

Figure 4.19 Comparison of different Parameters

The CO is highest at ICS 3 whose efficiency is the lowest. The efficiency doesn't show the trend at ICS 2 as it has the highest efficiency but ICS 5 emits the lowest CO. The PM emission is highest for ICS 5 while ICS 2 has the lowest.

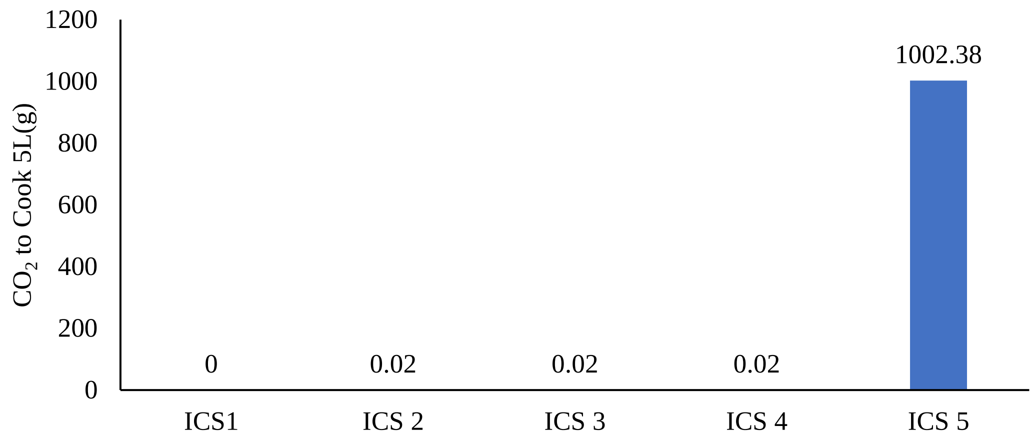

Figure 4.20 CO_2 to Cook

Generally, Carbon dioxide is produced after the complete combustion of the biomass. Incomplete combustion produces carbon monoxide while complete combustion produces carbon dioxide.

Apart from ICS 5, the carbon dioxide emission is insignificant compared to other pollutant parameters.

The high-power emission shall be considered to compare the different types of emission at high power i.e., the average of cold start and hot start. The comparative illustration is shown in the below Figure 4.21.

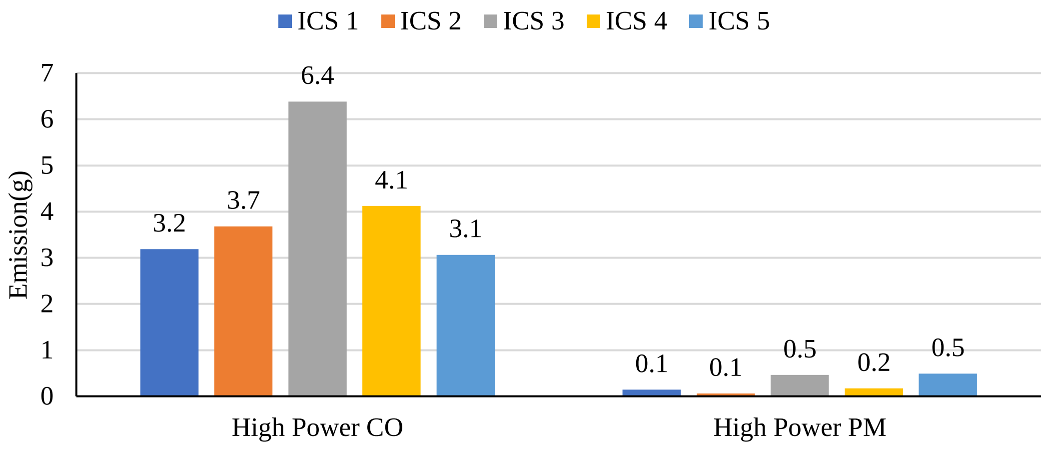

Figure 4.21 High Power Emission

It shows the same trend as Emission to cook. ICS 3 has the highest CO emission. while ICS 1 has the lowest high power CO emission.

ICS 3 has the second highest emission of PM2.5. The ICS 5 emits highest PM2.5 emission as the PM 2.5 to cook.ICS2 has the lowest PM2.5 while ICS 1 has the lowest high power CO emission.

The low power emission shall be considered to compare the different types of emission. Different type of emission factors is emitted during the simmering phase of the Water Boiling Test (WBT). The emission shows that the CO and PM 2.5 are emitted in the Figure 4.22.

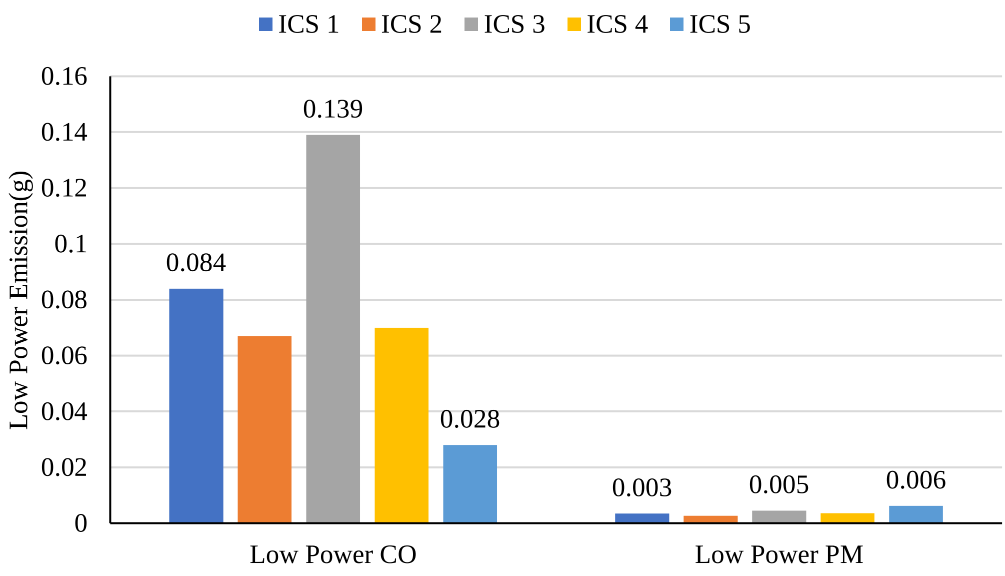

Figure 4.22 Low Power Emission

The Low Power CO follows the same pattern as that of CO to cook or high-power CO.

The PM followed the similar parameters except ICS 5 emits the highest PM as similar pattern to the PM to cook.

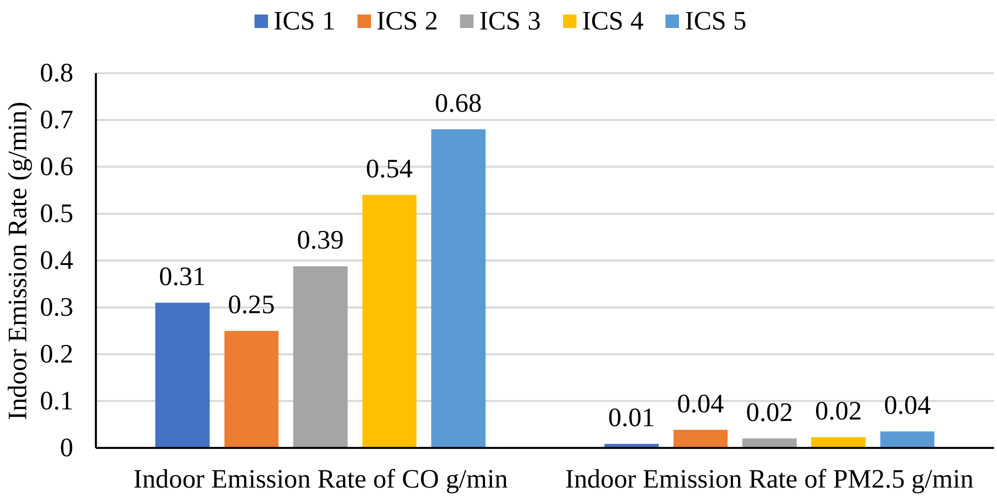

Figure 4.23 Indoor Emission Rate Comparison

This Indoor Emission Rate of CO follows the similar trend to CO to cook, High Power and Low Power CO.ICS 3 has the highest indoor emission rate of CO and ICS 5 has the lowest value. The indoor emission rate of PM2.5 follows the same pattern as other PM 2.5 factors.ICS 5 emits the highest PM2.5 which is followed by ICS 3.ICS 2 emits the lowest PM2.5 among the all ICS.

4.1.7 Financial Analysis for Five ICS

The financial analysis is compared taking per capita of consumption.

The below are the parameters that were considered during the financial analysis inTable 4.2

Table 4.2 Table for financial analysis

ICS	Initial Cost	Operation &Maintenance Cost	Fuel Cost (Kg)/person/year	Lifetime(yrs.)
ICS 1	6780	350	5280	4
ICS 2	15000	700	7250	4
ICS 3	2825	200	4650	3
ICS 4	5650	500	3600	3
ICS 5	5650	500	3660	5
Traditional Stove	1000	100	9120	3

Different Parameters are calculated taking

i=10%

The IRR takes into account the same amount of return as it provides on the first year. So, a new analysis method of Modified IRR(MIRR) is taken into account such that the real-world value is determined. The financial analysis is in Table 4.3

Table 4.3 Financial Analysis Table

Financial Analysis	ICS 1	ICS 2	ICS 3	ICS 4	ICS 5
Discounted Payback Period(yrs.)	2.2	NA	0.6	1.3	1.4
Internal Rate of Return (IRR)	46%	(28%)	125%	80%	79%
Modified Internal Rate of Return (MIRR)	30%	(18%)	68%	49%	48%
Net Present Value (NPV)	6274	(10381)	7184	8313	8150

From the financial point of view not considering the other factors such as emission and efficiencies ICS 3 has the highest return in every parameter while ICS 1 has the lowest as it uses Charcoal as a fuel which can provide high specific energy but the cost of the fuel is also very high. The ICS 2 has highest efficiency but the financial parameters are in negative which shows that the stove is not suitable in context of cost. The MIRR of ICS 3 and ICS 4 are comparative while that of ICS 5 follows them. The absolute NPV is highest for ICS 4. Overall ICS 4 shows a balance between efficiency and the financial parameters. It follows the ICS 2 in case of efficiency while ICS 4 has the strong financial parameters among all of the five improved cooking stoves.

Risk Analysis

Monte Carlo Simulation was performed for risk analysis and found out the probability of Breakeven NPV for five different ICS along with the probability of calculated NPV of five different ICS. Monte Carlo simulation was performed for different ICS for different fuel. Cost and discount rate was taken as Normal distribution with Standard deviation 10%. For Operation and Maintenance Triangular distribution while for cost it is lognormal as the cost is always positively skewed and mayn't be mean centered.

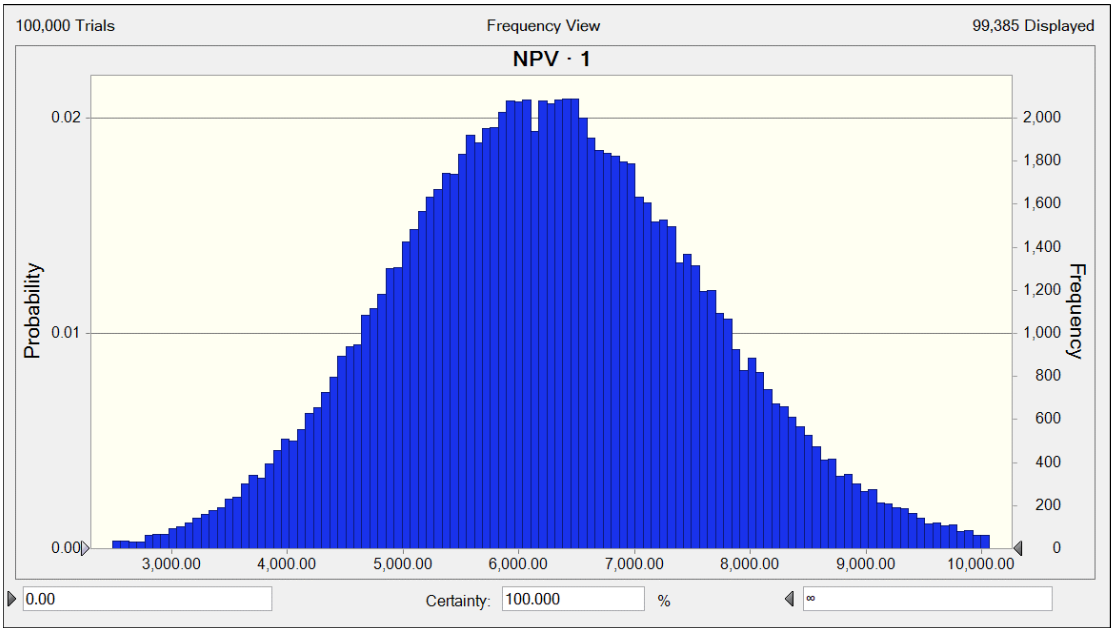

Figure 4.24 Probability of Breakeven NPV for ICS 1

This shows that there is 100% certainty that the ICS 1 will surpass breakeven point. So, ICS 1 will have positive Net Present value (NPV).

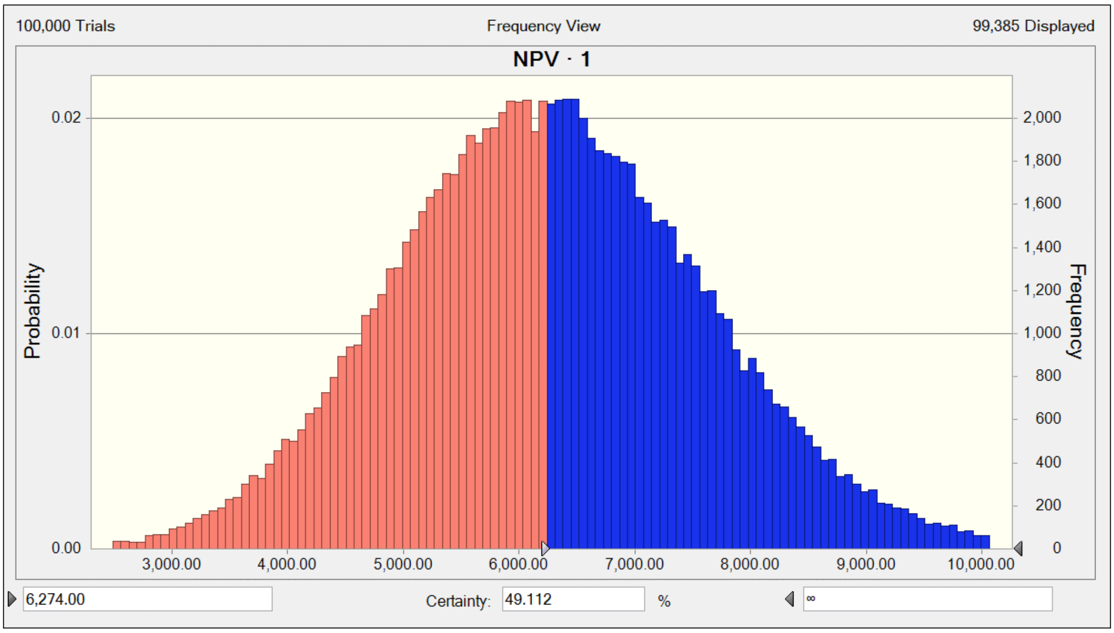

Figure 4.25 Probability for NPV calculated for ICS 1

Despite a 49.12% likelihood of attaining an NPV of 6274, the absolute certainty of zero NPV across simulations highlights substantial risk, demanding thorough evaluation and risk mitigation strategies before decision-making.

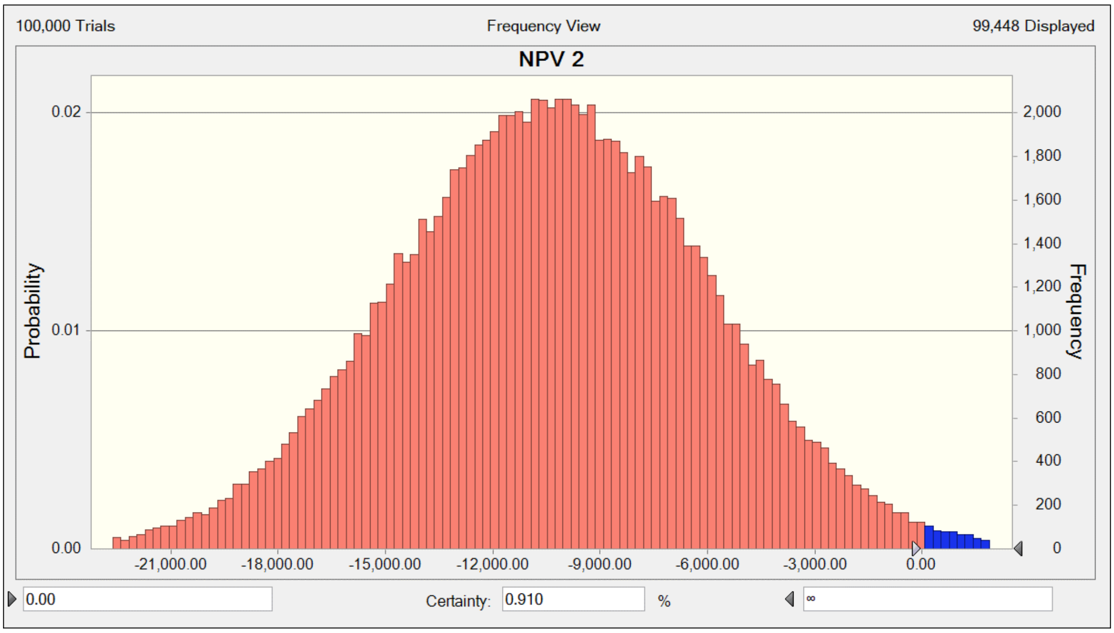

Figure 4.26 Probability of Breakeven NPV of ICS 2

The probability of breakeven for ICS 2 is very unlikely with a probability of 0.91%. It shows that the ICS 2 has the very less chance of being profitable compared to TCS due to its initial investment cost.

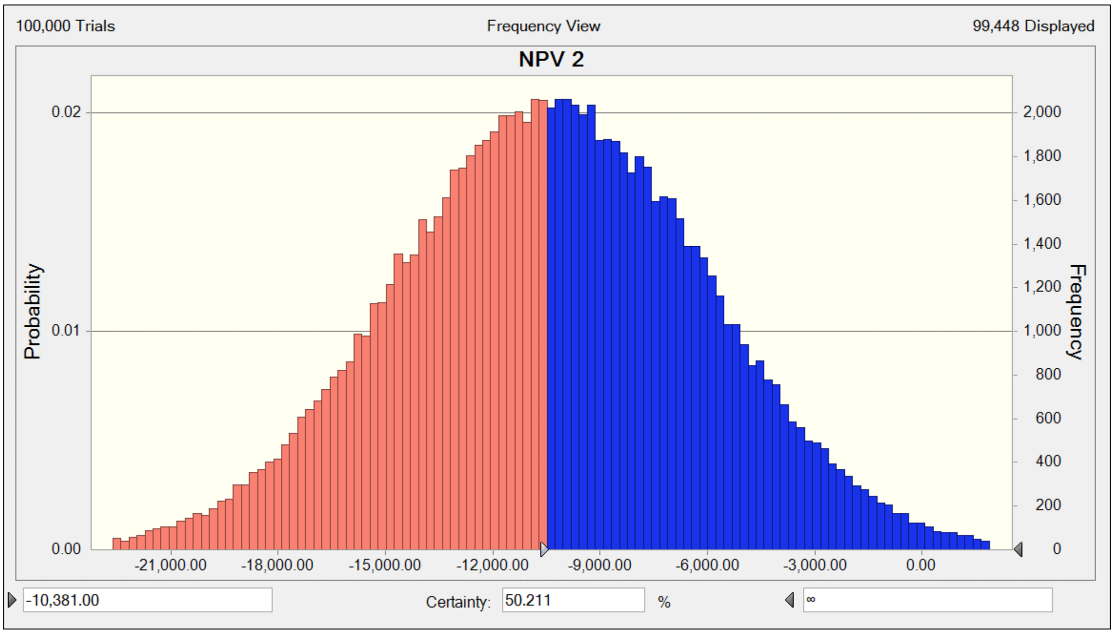

Figure 4.27 Probability of Calculated NPV for ICS 2

The probability that it has negative NPV of (10381) is 50.2%. These findings underscore a higher likelihood of incurring negative NPV (10381) compared to reaching the breakeven point, signifying a considerable risk of loss associated with the investment. This necessitates a comprehensive risk assessment and mitigation strategy to address potential financial setbacks before making informed decisions regarding the project's feasibility and viability.

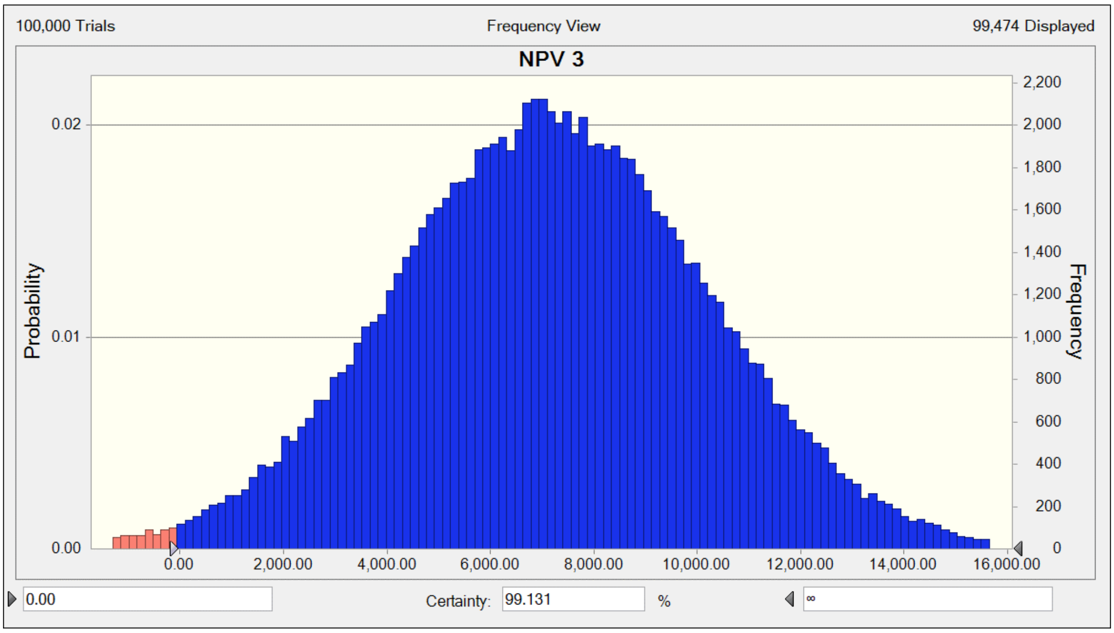

Figure 4.28 Probability of Breakeven NPV for ICS 3

The probability of Breakeven is high for ICS 3 which is 99.31%. It shows a probability that at least the cookstove will have breakeven.

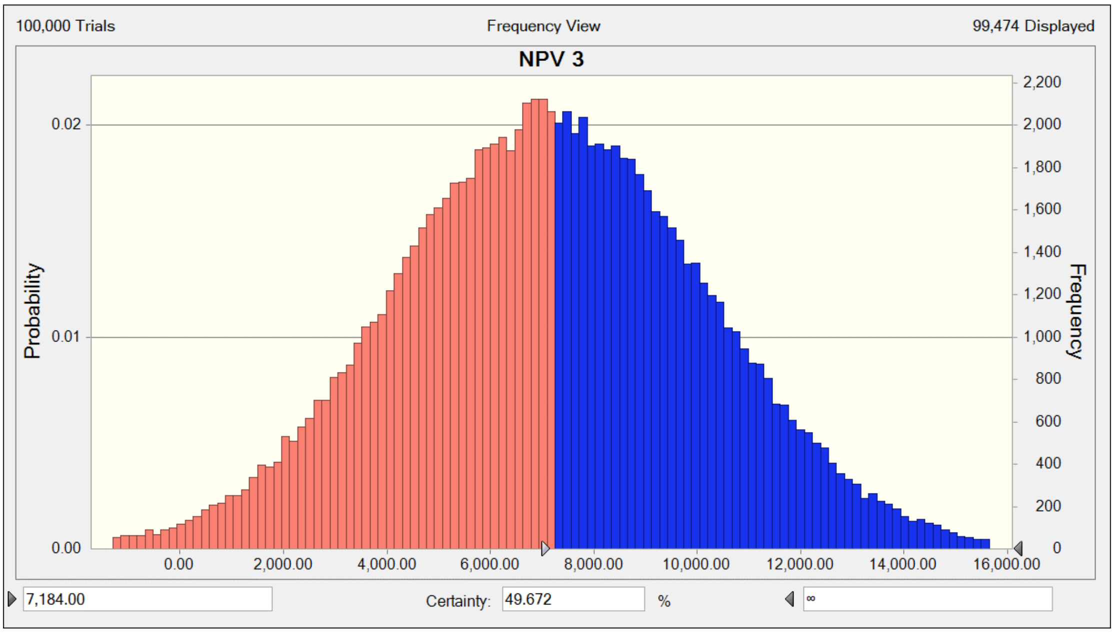

Figure 4.29 Probability of Calculated NPV for ICS 3

The calculated NPV has a probability of 49.6% of occurrence of the calculated NPV of 7184.

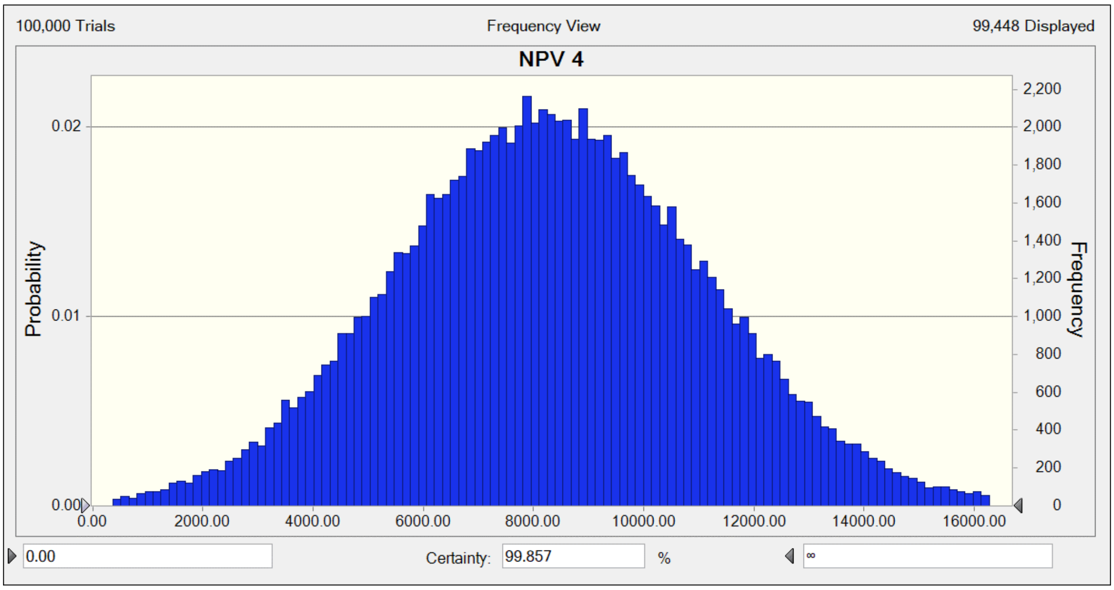

Figure 4.30 Probability of Breakeven NPV of ICS 4

The probability of Breakeven is high for ICS 4 which is 99.85%. It shows a probability that at least the cookstove will have breakeven.

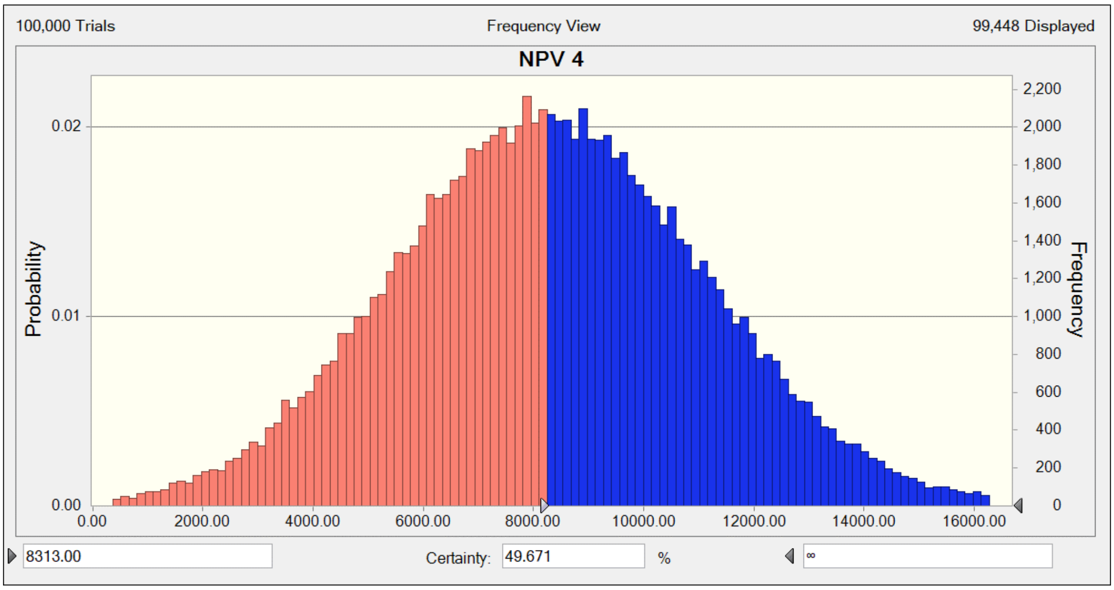

Figure 4.31 Probability of Calculated NPV of ICS 4

These outcomes present an encouraging picture, highlighting a significant probability of both achieving a positive NPV and attaining the breakeven point. The high likelihoods 49.67% for positive NPV and 99.85% for breakeven—underscore a promising potential for favorable financial returns or, at minimum, a balanced outcome.

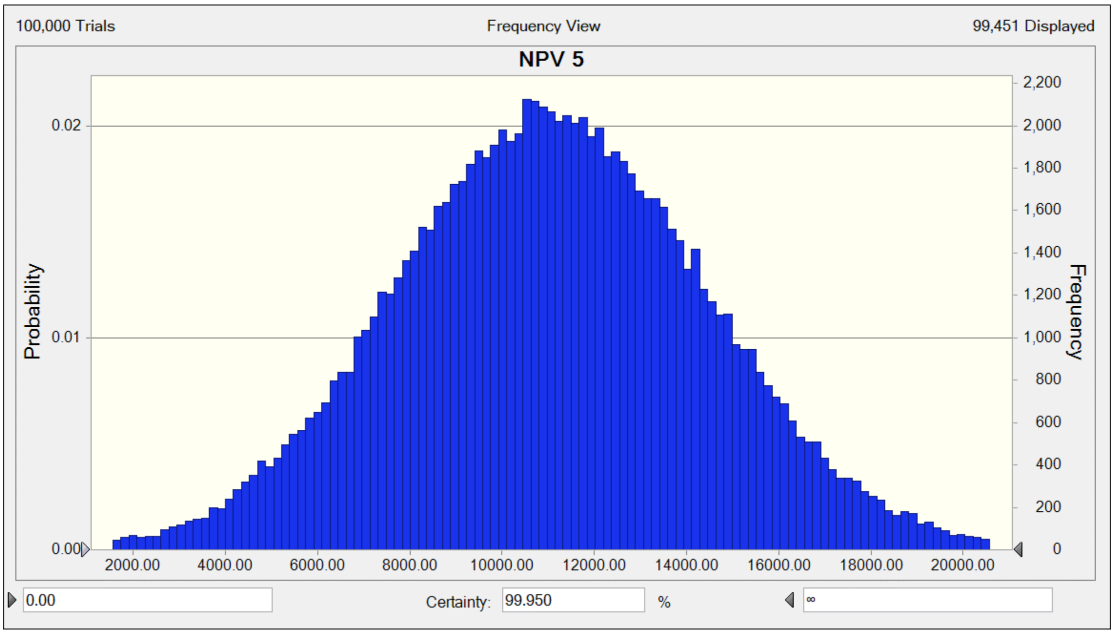

Figure 4.32 Probability of Breakeven NPV of ICS 5

The probability of Breakeven is high for ICS 5 which is 99.95%. It shows a probability that at least the cookstove will have breakeven.

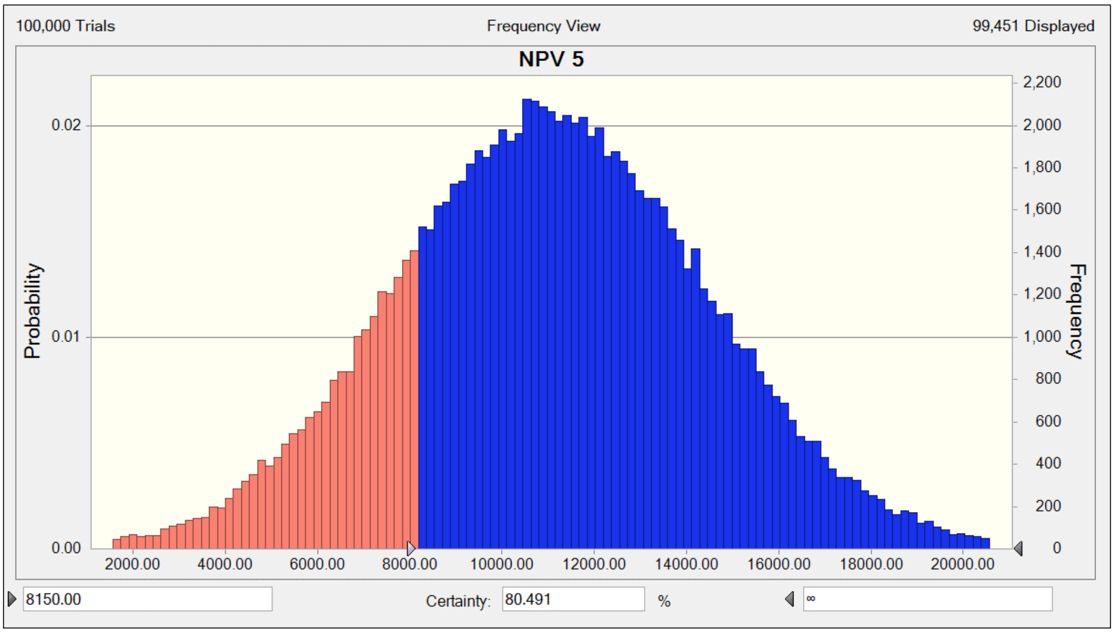

Figure 4.33 Probability of Calculated NPV for ICS 5

ICS 5 has 80.49% likelihood of attaining an NPV of 6274, the absolute certainty of zero NPV across simulations highlights substantial risk, demanding thorough evaluation and risk mitigation strategies before decision-making.

4.1.8 Benefit Cost Analysis for Five ICS

The fuel consumption for traditional stove (TCS) per capita is 912 kg/yr and efficiency of stove was taken as per Table 3.1.The efficiency of TCS was taken as 10% while energy derating factor is 10%. The market price of carbon is considered as $5/t$CO_2$ equivalent. The net benefits of the different ICS compared to the TCS is as in Figure 4.34

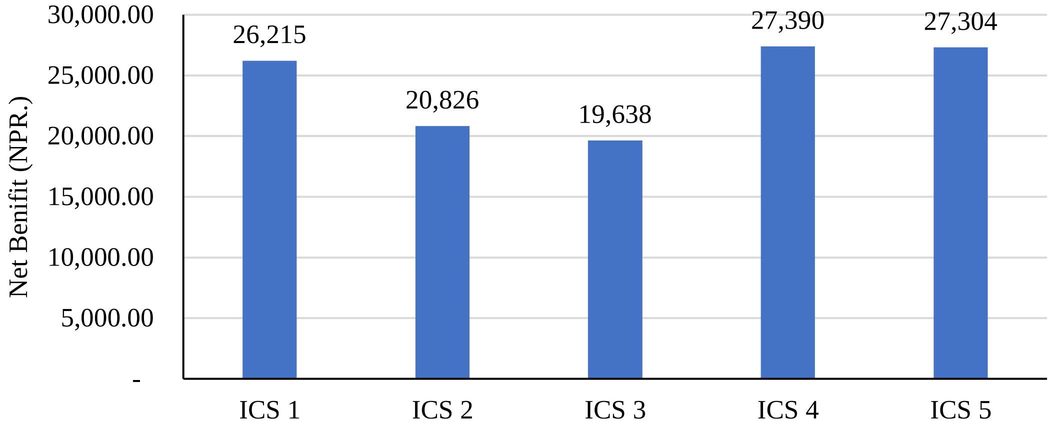

Figure 4.34 Net Benefit of Different ICS

The Net Benefit of ICS 4 is high while ICS 3 is found to be lowest among them.

The Stove cost and Operation Cost were considered as the Fixed Cost and Variable cost respectively. The fuel saving and Carbon Emission Saving (in terms of CO_2eq) was considered as the Benefits.

The benefit cost analysis of ICS 3 is high because of its very low initial cost. The quantitative B-C ratio is shown in the Table 4.4 below;

Table 4.4 B-C Ratio of different ICS

ICS	B-C Ratio
ICS 1	4.59
ICS 2	1.49
ICS 3	9.30
ICS 4	5.46
ICS 5	5.44

From the above analysis, it is known that ICS 3 has the best B-C ratio despite its very low efficiency among the ICS. It is because the fixed and variable cost for the stove is very low compared to that of others. The emission is very high in case of ICS 3 and efficiency is very low.ICS 4 follows the B-C ratio.

From the economical point of view the Net Benefit of ICS 4 is high while for Benefit Cost ratio is second to ICS 3. For cookstove selection decision Net Benefit is prominent factor among all.

4.1.9 Marginal Abetment Cost

The marginal abatement cost is calculated using Net Benefits from the carbon savings or credit as agreed per unit and is show in Figure 4.35 below;

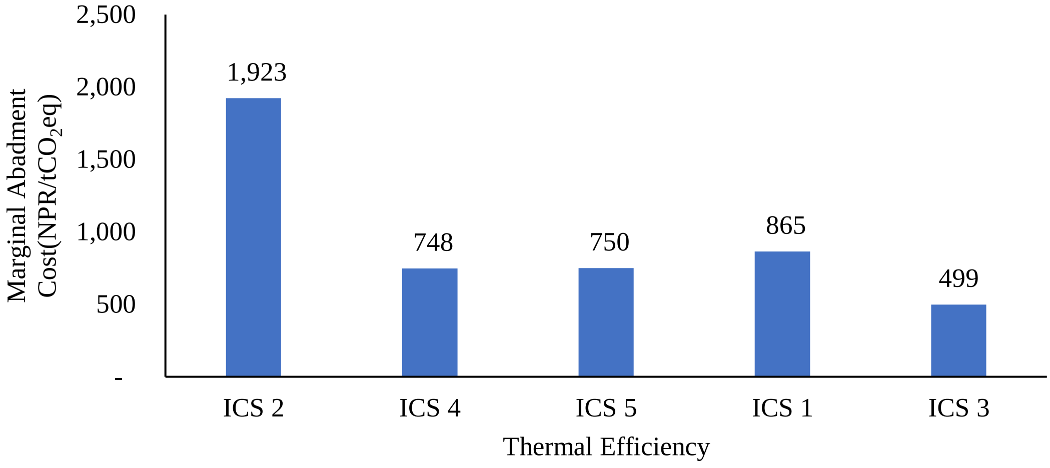

Figure 4.35 Marginal Abetment cost

From the social benefit and marginal abetment cost, ICS 3 is found to be beneficial.ICS 4 follows the ICS 3 in the benefit. The least Marginal Abetment cost is NPR 499/tCO_2eq while ICS 2 has the highest is NPR 1923/tCO_2eq which is very high compared to the agreement with AEPC.From the net benefit and economic point of view ICS 4 has the best that saves more fuel and cost during its operation.

4.2 Selection of Stove

Different Parameters are compared above and an insight is developed. But all the major factors are in a different scale and hence a fair comparison is made among different factors. The normalized value of different parameters is shown in Table 4.5 below;

Table 4.5 Normalized Value of different ICS

Normalized Value							
ICS	Efficiency	Turn Down Ratio	Specific Fuel consumption	Emission	Cost	Marginal Abtement cost	Average
ICS 1	0.39	0.98	0.79	0.73	0.68	0.74	0.66
ICS 2	1	0	1	0.88	0	0	0.59
ICS 3	0	0.78	0	0.13	1	1	0.39
ICS 4	0.48	1	0.82	0.73	0.77	0.83	0.72
ICS 5	0.44	0.58	0.62	0.50	0.77	0.82	0.58

Considering different parameters where Efficiency and Turn down ratio are normalized value while other factors are considered after transformed normalized value. The average is calculated using weighted average method. From the above Table 4.5, it is found that considering different factors and parameter ICS 4 has the highest average value and it is selected for experiment.

4.3 Experimental Results

From the above comparative analysis on different parameters, although ICS 3 has high IRR and Benefit Cost Ratio, the efficiency of the ICS is very low compared to others while emission is very high.ICS 3 is followed by ICS 4 in every financial factor and has highest Net Present Value. The normalized value is higher for ICS 4. ICS 4 is a Force draft stoves from Husk Power Nepal. This stove was subjected with three different fuels i.e., Charcoal, Firewood and Wood Pellet and experiment was performed.

4.3.1 Firepower

The Firepower of ICS 4 for different fuel has been shown in Figure 4.36

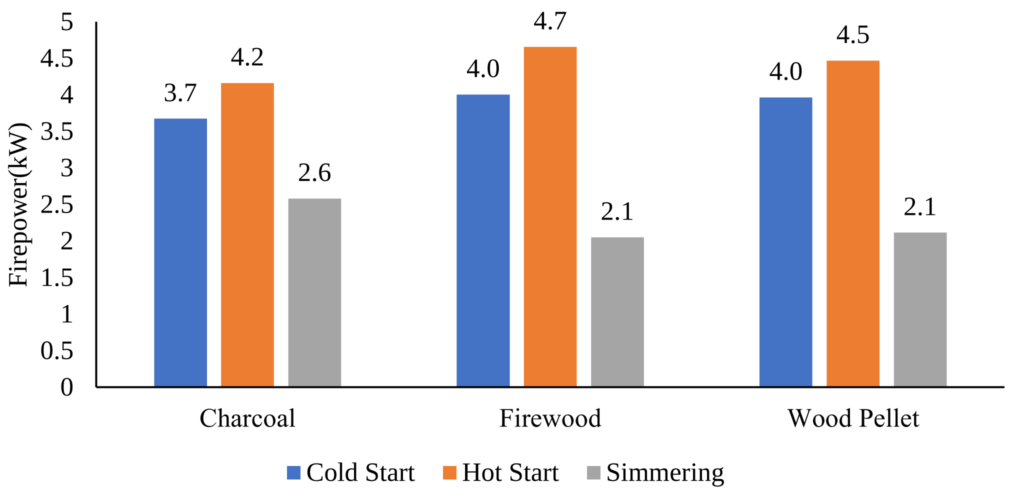

Figure 4.36 Comparison of Firepower of different fuel

From the above chart, Charcoal has the lowest firepower while firewood and wood pellet follow. It shows that Charcoal burns less per time providing similar energy to burn.

Figure 4.37 Comparison of Firepower at different phase for different fuel

The above Figure 4.37 shows the Firepower at different start. More energy is required for cold and hot start compared to that of simmering. The above compassion shows that the firepower for simmering is very lower compared to that of cold and hot start. The firepower is less for experiment compared to that of secondary data for the same fuel i.e., firewood. This is because the secondary data are taken from lab tested condition, this is due to less fuel burned for the same period of time during the experiment. The firepower follows similar pattern in both conditions

4.3.2 Time to Boil

The time to boil for Cold start and Hot start were recorded and is illustrated in Figure 4.38.

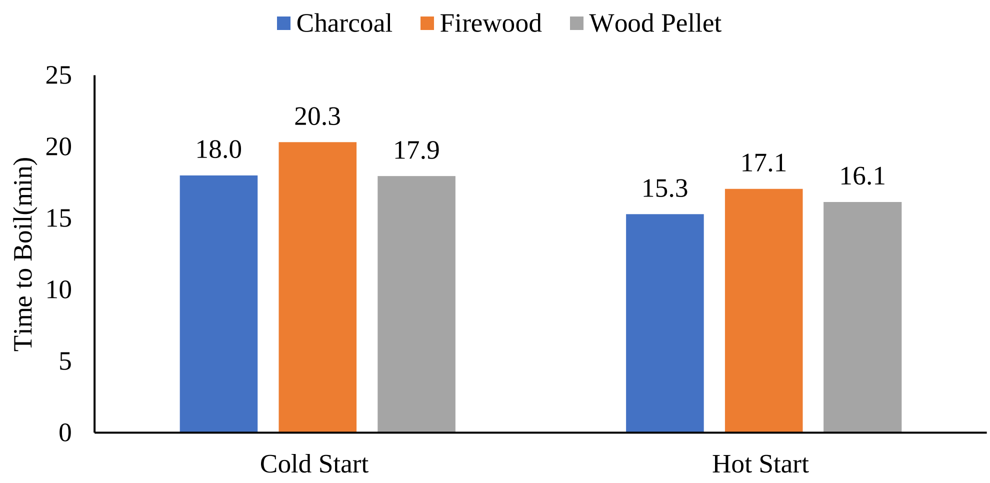

Figure 4.38 Time to Boil for different Fuel at different phases

This shows that time to boil is higher in case of cold start. The cold start starts at ambient temperature and hence require more time to boil the water. But at the hot start, the vessel is already heated and hence requires less time to boil. From the above illustration it is clear that, at cold start Charcoal takes less time to boil while Firewood takes most time to boil. There is no boiling of water during the simmering of water. The pattern is similar for different ICS and different fuel. The time to boil in experiment data is high, it is because of various factor.one of them is the lab tested conditions are in controlled environment while that of experiment, the controlled environment is difficult to achieve.

4.3.3 Thermal Efficiency

The Thermal efficiency of the ICS was calculated by using water boiling test spreadsheet. The efficiency for stove at different fuel is as shown in Figure 4.39

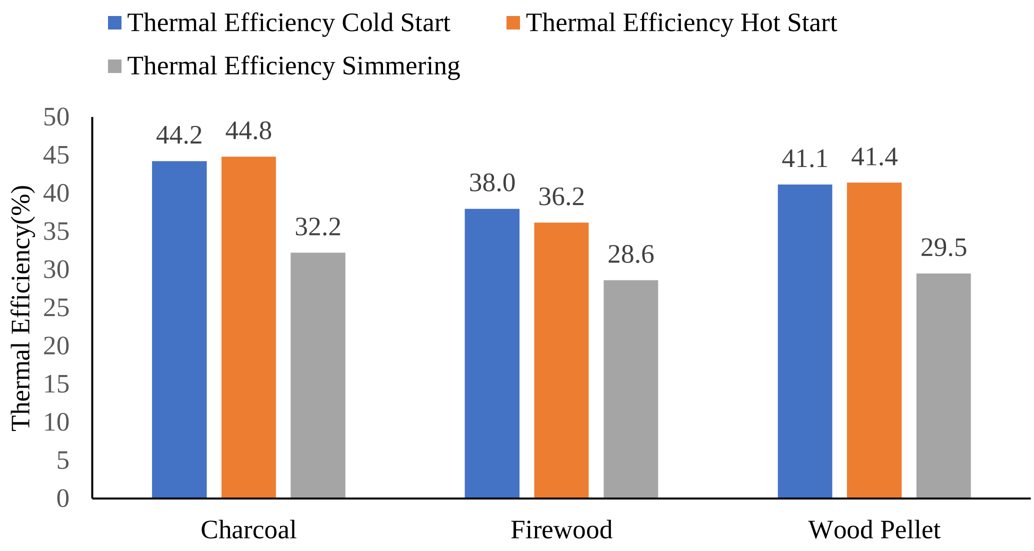

Figure 4.39 Thermal efficiency for different fuel

Charcoal has the highest thermal efficiency whereas firewood has lowest thermal efficiency among them. The energy content is generally higher for Charcoal and hence it effects the thermal efficiency.

Similarly for different phases the data obtained are segregated and he thermal efficiency for different phases is shown in Figure 4.40

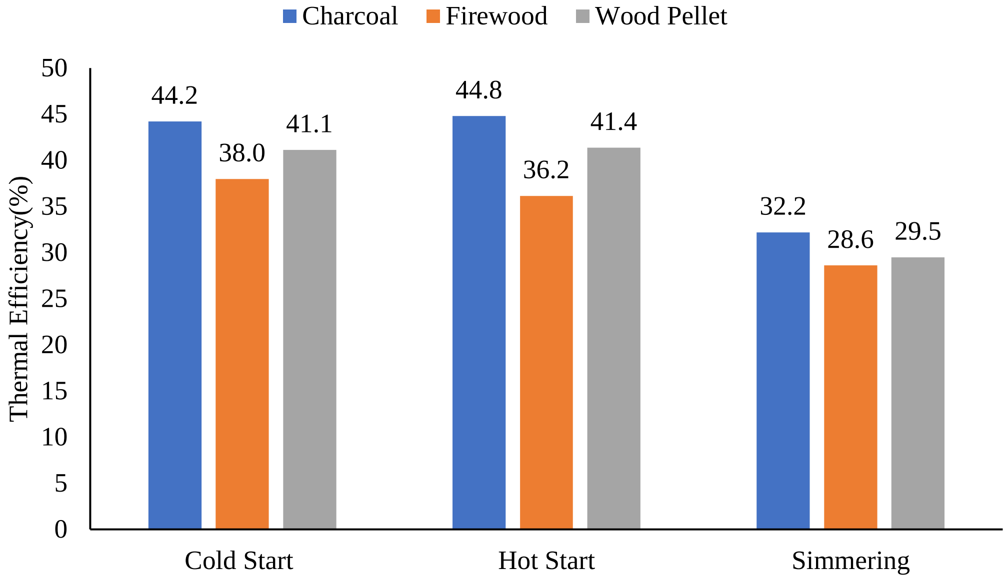

Figure 4.40 Thermal Efficiency at different phase for different fuel

The high-power efficiency is higher than that of simmering efficiency in general ICS. It shows the similar pattern as that of other ICS. The thermal efficiency of lab tested and experiment are near equal for all phases.

The cold start and hot start efficiency are slightly lesser than that of lab tested while simmering efficiency is higher. It shows that overall efficiency of the stove is nearly same for both lab data and experimental data.

4.3.4 Turn Down Ratio

The ratio of high and low power is a turn down ratio. The turn down ratio for stoves for different fuel is shown in Table 4.6

Table 4.6 Turn Down Ratio for Different fuel

Fuel Type	Turn Down Ratio
Charcoal	1.43
Firewood	1.42
Wood Pellet	1.92

From the above table, it is shown that the Charcoal has the highest turn down ratio while wood pellet and Fuelwood has similar turn down ratio. Charcoal has the highest turn down ratio, ability of the stove to be "turned down" from boil to simmer phase, and the extent to which stove firepower can be controlled.

The turn down ratio is significantly lower in experiment due to less high-power firepower compared to that of lab tested data. This implies that the high-power firepower is less for the experimental data compared to that of lab tested data.

The turn down ratio and firepower were plotted as shown in Figure 4.41.

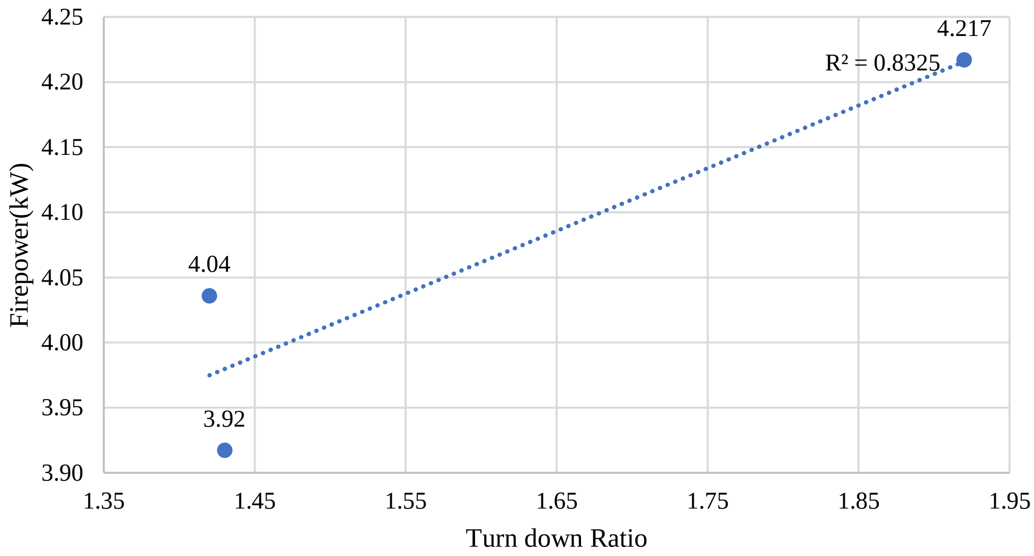

Figure 4.41 Firepower and Turn down Ratio for different Fuel

The Scatter plot of the Firepower and Turn Down Ratio shows that the R^2 value is 0. 8325.The fit is a strong one. It shows that the firepower and turn down ratio are linearly fit. The turndown ratio and Firepower are exponentially corelated which shows the upward trend. Firepower depends upon size, as the size of the same stove remains constant.

4.3.5 Specific Fuel Consumption

The fuel consumption is least for the Charcoal while fuelwood consume high specific fuel at high power phase The Specific Fuel Consumption for different fuel is shown in Figure 4.42

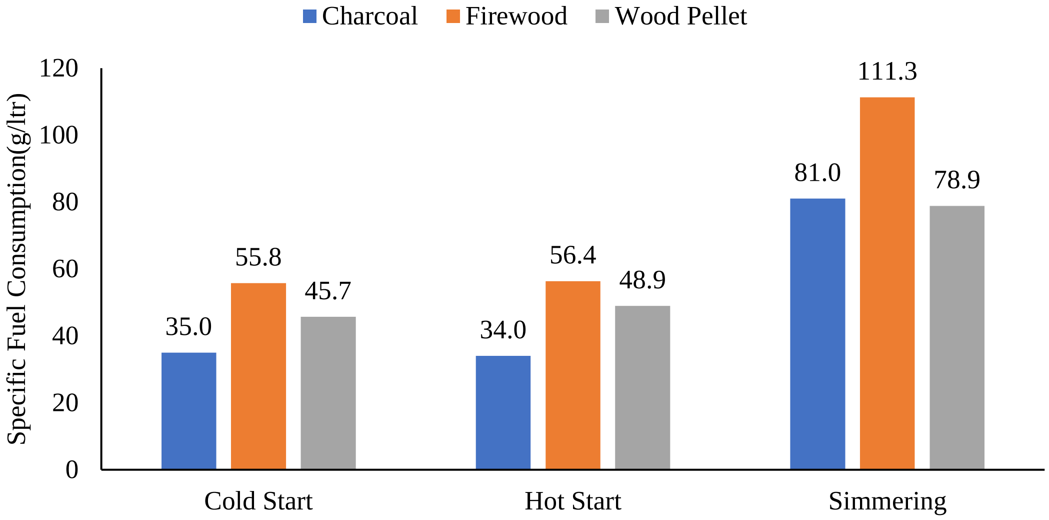

Figure 4.42 Specific Fuel Consumption for different fuel

The above bar graph shows that firewood has the highest specific fuel consumption and Charcoal has the lowest specific fuel consumption among all the fuels. The fuel consumption was high in simmering phase because boiling of water takes place continuously for around 45 minutes at a constant temperature. For the Charcoal, the fuel consumption is comparable with high power and low power. The specific fuel consumption is similar for both conditions. The specific fuel consumption for cold and hot start is higher for experimental data whereas simmering consumption is less compared to that of secondary data.

4.3.6 Financial Analysis of ICS 4

The financial analysis is compared taking per capita of consumption.

The below are the parameters that were considered during the financial analysis for ICS 4 with different fuel type as is shown in Table 4.7

Table 4.7 Table for Financial Analysis for ICS 4

Fuel	Initial Cost	Operation &Maintenance Cost	Fuel Cost (Kg)/person/year	Lifetime(yrs.)
Charcoal	5650	500	4100	3
Firewood	5650	500	3600	3
Wood Pellet	5650	500	5750	3
Traditional Stove	1000	100	9120	3

Different Parameters are calculated taking

i=10%

The IRR takes into account the same amount of return as it provides on the first year. So, a new analysis method of Modified IRR(MIRR) is taken into account such that the real-world value is determined.

Different fuels on the stove are compared with Traditional stoves and hence the return value is taken into accounts from them.

The financial analysis for ICS 4 with different fuel is tabulated in Table 4.8

Table 4.8 Financial Analysis Table for ICS 4

Financial Analysis	Charcoal	Firewood	Wood Pellet
Discounted Payback Period(yrs.)	1.4	1.3	4.3
Internal Rate of Return (IRR)	69%	80%	(9) %
Modified Internal Rate of Return (MIRR)	44%	49%	(3) %
Net Present Value (NPV)	4100	3600	(1788.18)

From the financial point of view not considering any other factors. Firewood has the highest IRR, MIRR and NPV.The Charcoal and wood pellet follows respectively. ICS 4 can be used with different fuel and hence has high Net Present values for all fuel.

Risk Analysis of ICS 4

Monte Carlo simulation was performed for ICS 4 for different fuel. Cost and discount rate was taken as Normal distribution with Standard deviation 10%. For Operation and Maintenance Triangular distribution while for cost it is lognormal as the cost is always positively skewed and mayn't be mean centered.

These outcomes present an encouraging picture, highlighting a significant probability of both achieving a positive NPV and attaining the breakeven point. The high likelihoods 49.67% for positive NPV of 3600 and 99.85% for breakeven—underscore a promising potential for favorable financial returns or, at minimum, a balanced outcome. The outcomes are similar as Figure 4.30 & Figure 4.31.

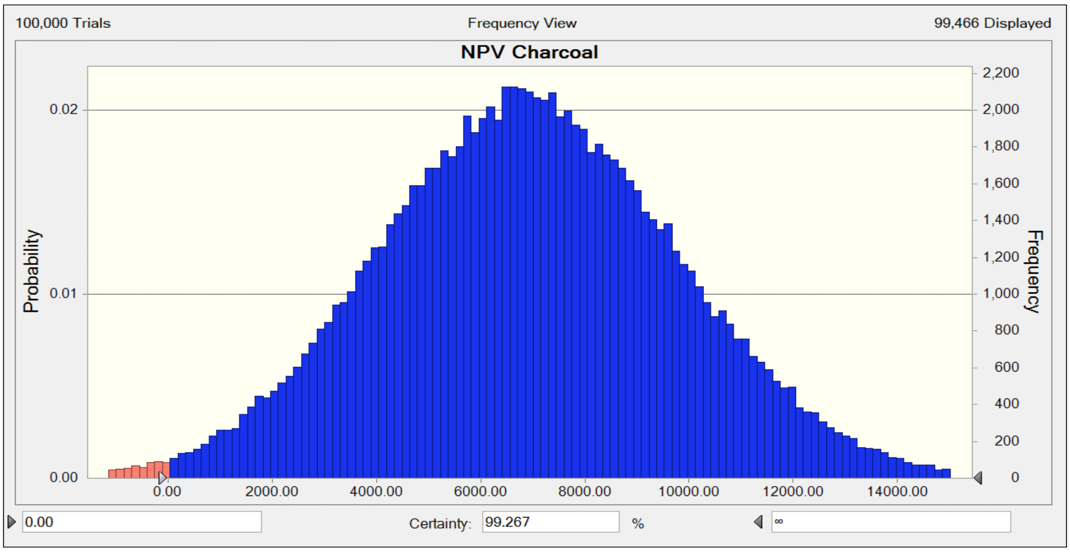

Figure 4.43 Probability of Breakeven NPV for charcoal

The probability of Breakeven is high for ICS 4 which is 99.85%. It shows a probability that at least the cookstove will have breakeven.

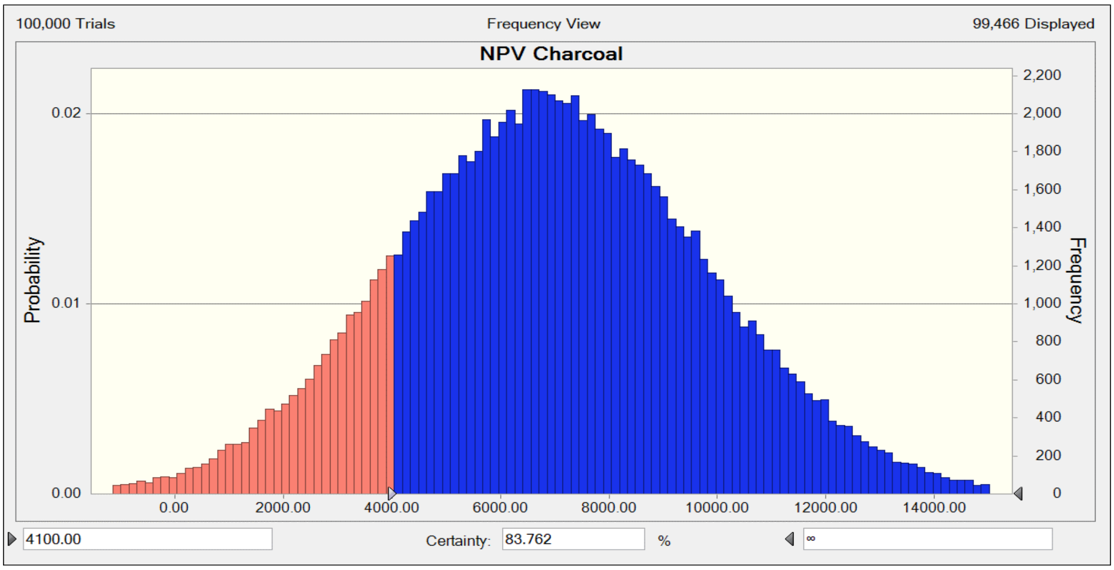

Figure 4.44 Probability of Calculated Breakeven for Charcoal

These outcomes present an encouraging picture, highlighting a significant probability of both achieving a positive NPV and attaining the breakeven point. The high likelihoods 81.76% for NPV of 4100 and 99.26% for breakeven—underscore a promising potential for favorable financial returns or, at minimum, a balanced outcome.

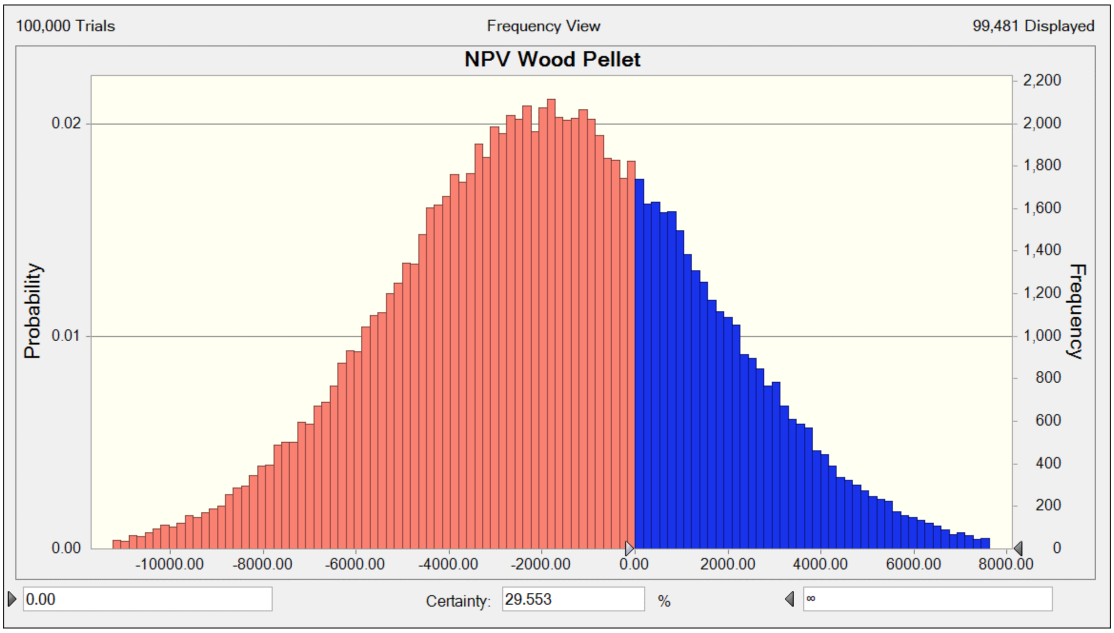

Figure 4.45 Probability of Breakeven NPV for Wood Pellet

The probability of breakeven for ICS 2 is very unlikely with a probability of 29.55%. It shows that the ICS 2 has the very less chance of being profitable compared to TCS due to its initial investment cost.

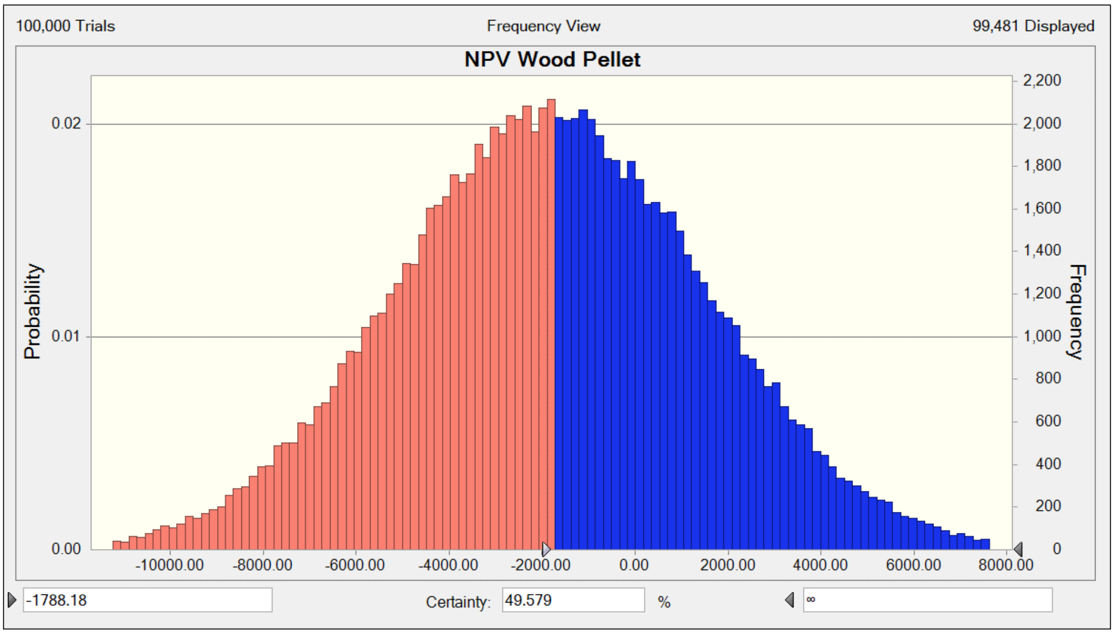

Figure 4.46 Probability of Calculated NPV for Wood Pellet

The probability that it has negative NPV of (1788.18) is 49.57%. These findings underscore a higher likelihood of incurring negative NPV (1788.18) compared to reaching the breakeven point, signifying a considerable risk of loss associated with the investment. This necessitates a comprehensive risk assessment and mitigation strategy to address potential financial setbacks before making informed decisions regarding the project's feasibility and viability.

4.3.7 Benefit Cost Analysis of ICS 4

The net benefit for different fuel compared to TCS is shown in Figure 4.47

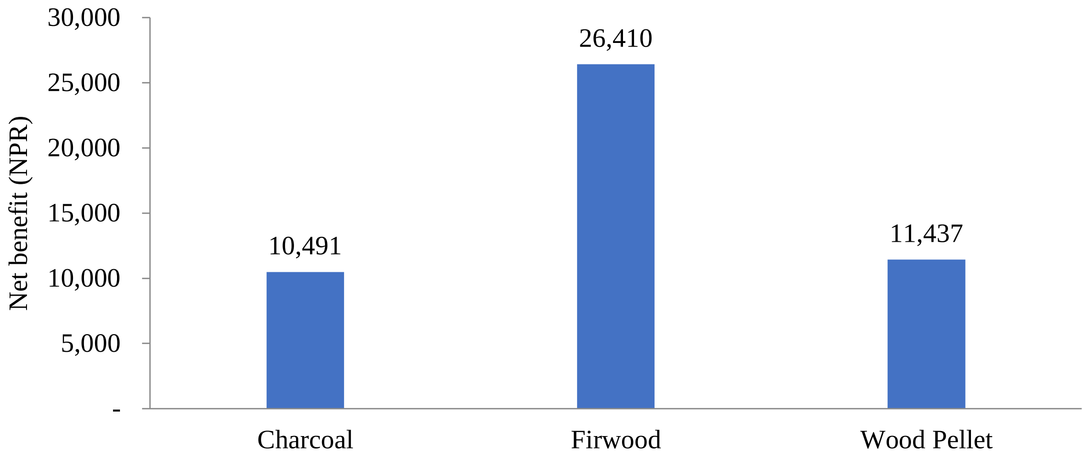

Figure 4.47 Net Benefit of ICS 4 for different fuels

The Net Benefit of Firewood is high while charcoal is found to be lowest among them.

The Stove cost and Operation Cost were considered as the Fixed Cost and Variable cost respectively. The fuel saving and Carbon Emission Saving (in terms of CO_2eq) was considered as the Benefits.

The parameters for Benefit-Cost Analysis are as per in different ICS. All the parameters are kept constant and different fuel was used for ICS 4.

The quantitative B-C ratio is shown in the Table 4.9

Table 4.9 B-C Ratio for ICS 4

Fuel	B-C Ratio
Charcoal	2.09
Firewood	5.26
Wood Pellet	3.07

From the above analysis, it is known that Firewood has the best B-C ratio despite its low efficiency among the fuel used. It is because the fuel cost for the fuel is very low compared to that of others. The cost of firewood is generally lower compared to that of Charcoal and wood pellet.

4.3.8 Marginal Abetment Cost of ICS 4

The marginal abatement cost of three different fuel for Force Draft wood stove (ICS 4) were calculated as per the same methos as of Five ICS and is shown in Figure 4.48

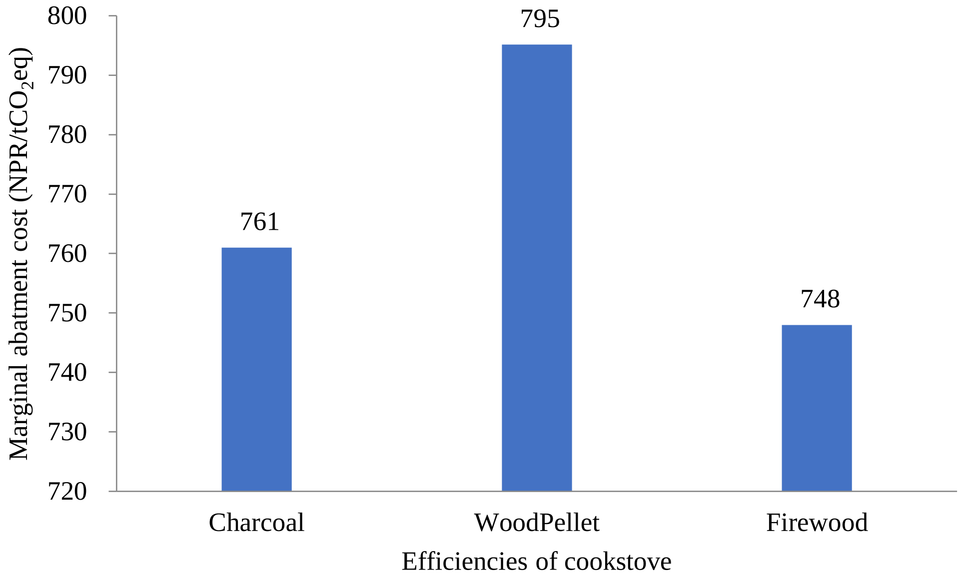

Figure 4.48 Marginal Abetment Cost of ICS 4 for different fuel

From the social benefit and marginal abetment cost, firwood is found to be beneficial. The least Marginal Abetment cost is NPR 748/tCO_2eq for firewood while Wood Pellet has the highest NPR 795/tCO_2eq which is high compared to the agreement with AEPC.From the net benefit and economic point of view Firewood has the best that saves more fuel and cost during its operation.

CHAPTER FIVE: CONCLUSIONS AND RECCOMENDATIONS

5.1 Conclusions

Following conclusion has been drawn from the study

- The Force Draft Wood Pellet stove (ICS 2) exhibits a thermal efficiency of 47.25% and the highest simmering efficiency at 50.34%. Although boasting high thermal efficiency and firepower, it maintains a low turn-down ratio of 1.14, nearly approaching unity. Conversely, the Natural Draft Wood stove (ICS 3) showcases the lowest fuel efficiency, albeit with a high-power efficiency of 29.39%
- Among the fuels used for the Force Draft wood stove (ICS 4), charcoal demonstrates the highest thermal efficiency at 44.51%, followed by wood pellets at 41.26%, and firewood at 37.91%, consistent with lab-tested efficiency. Despite its efficiency, charcoal displays a low turn-down ratio, whereas wood pellets exhibit the highest turn-down ratio of 1.92, with specific fuel consumption being lower for charcoal and higher for firewood
- Emission factors display a significant correlation, with R2 values of 0.856 for CO and 0.9678 for PM2.5. Initial emission reductions are observed, with Natural Draft Charcoal Stove (ICS 1) yielding a reduction of 3.52 tCO_2eq in the first year, while Natural Draft wood stove (ICS 3) exhibits the lowest reduction at 1.92 tCO_2eq. Force Draft wood stove using charcoal (ICS 4) achieves the highest emission reduction of 3.76 tCO_2eq, closely followed by wood pellets at 2.21 tCO_2eq
- Natural draft wood stove (ICS 3) demonstrates high IRR (125%) and MIRR (68%) due to low initial and operational costs despite lower efficiency. Force draft wood stoves (ICS 4) &Natural draft wood stove (ICS 5) exhibit substantial NPVs (NPR 8313.68 & NPR 8150) and comparable IRR/MIRR to ICS 3. Conversely, Force Draft wood pellet stove (ICS 2) shows negative IRR (28%) and NPV (NPR (10381.80)) with the probability of 50.2% while breakeven NPV is 0.9%, suggesting its unsuitability. ICS 4 yields the highest IRR (80%) for firewood but negative IRR ((9%)) for wood pellets, indicating wood pellets' unsuitability due to negative NPV (NPR (1788.18)), while firewood presents the highest NPV (NPR 3600) despite lower efficiency. Natural draft wood stove (ICS 3) boasts a B-C ratio of 9.30, yielding a net benefit of NPR 19638, whereas Force draft wood stoves (ICS 4) and Natural draft wood stoves (ICS5) showcase B-C ratios of 5.46 and 5.44, with net benefits of NPR 27390 and NPR 27304, respectively. Firewood proves to be the most economical fuel, displaying the

highest net benefit (NPR 26410) and B-C ratio (5.26) alongside comparable carbon reduction and NPV

- The marginal abatement cost is lowest for Natural Draft wood Stove (ICS 3) at NPR 499/ tCO_2eq, followed by Force draft wood stove (ICS 4) at NPR 748/ tCO_2eq. Conversely, Force draft wood Pellet Stove (ICS 2) exhibits the highest abatement cost at NPR 1923/tCO2eq, despite its highest efficiency. Within ICS 4, wood pellets display a higher abatement cost at NPR 795/ tCO_2eq compared to firewood at NPR 748/ tCO_2eq
- Force draft Wood stove using firewood demonstrates the highest Net Present Value (NPR 3600), an 80% Internal Rate of Return (IRR), the highest net benefit (NPR 26,410), and the lowest marginal abatement cost (NPR 748/ tCO_2eq) among all fuels, recommending it as the preferred stove option

5.2 Recommendations

Following recommendations are provided

- Experiment for emission test with different fuel for different type of cookstove could be performed.
- Different fuel or variety of fuel found in different climate condition and region could be tested

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APPENDIX A

The thermal efficiency of five different ICS is shown as

ICS Model	Thermal Efficiency		
	Cold Start	Hot Start	Simmering
ICS 1	37.25	35.59	29.36
ICS 2	44.95	49.54	50.34
ICS 3	28.84	29.93	28.73
ICS 4	38.27	37.71	27.08
ICS 5	37.55	37.16	47.19

The turn down ratio of five different ICS is shown as

ICS Model	Turn Down Ratio
ICS 1	1.86
ICS 2	1.14
ICS 3	1.71
ICS 4	1.87
ICS 5	1.56

The specific fuel consumption of five different stove are as follows

	Specific Fuel Consumption(gm/liter)	Specific Fuel Consumption(gm/liter)	Specific Fuel Consumption(gm/liter)
	Cold Start	Hot Start	Simmering
ICS 1	52.62	53.02	142.22
ICS 2	47.62	43.23	118.22
ICS 3	70.96	70.57	98.04
ICS 4	51.81	51.35	124
ICS 5	56.4	53.57	93.58

Different parameters to be considered for B-C Analysis

Parameter	Value
Fuel Consumption for traditional stove for one person	912 Kg/year
Fuel Consumption for traditional stove for four-member family	3.65 tons/year
Efficiency of stoves	As per Table 3.1

Parameter	Value
Efficiency of TCS	10%
Efficiency Derating factor of ICS	10%
Market Price of Carbon	\$5/t CO_2eq
Dollar Exchange Rate	NPR 132

The Specific fuel consumption for ICS 4 using different fuel is as

Fuel Type	Specific Fuel Consumption(gm/liter)	Specific Fuel Consumption(gm/liter)	Specific Fuel Consumption(gm/liter)
	Cold Start	Hot Start	Simmering
Charcoal	34.60	34.22	36.48
Firewood	52.50	52.32	63.57
Wood Pellet	45.68	48.94	67.6

APPENDIX B






APPENDIX C

The water boiling calculation spreadsheet for Charcoal is shown in figure below

WATER BOILING TEST - VERSION 4.2.3	**TEST #**
All cells are linked to data worksheets, no entries are required	
Stove type/model	
Location	IOE Pulchowk Campus,Stove Testing Lab
Fuel description	Charcoal
Wind conditions	No wind; No wind; No wind;
Ambient temperature	25ºC; 24ºC; 24ºC; ºC; ºC; ºC; ºC; ºC; ºC; ºC

1. HIGH POWER TEST (COLD START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time to boil Pot # 1	min	19	17	18	17.99	0.8	4.6%
Temp-corrected time to boil Pot # 1	min	21	19	19	19	1.0	5.2%
Burning rate	g/min	9	10	9	9	0.6	6.9%
Thermal efficiency	%	45%	42%	45%	44.22%	1.72%	3.9%
Specific fuel consumption	g/liter	35	36	33	35	1.3	3.7%
Temp-corrected specific consumption	g/liter	38	38	36	37	1.1	3.0%
Temp-corrected specific energy cons.	kJ/liter	885	903	851	879	26.4	3.0%
Firepower	watts	3,478	3,957	3,582	3672.59	251.8	6.9%

2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time to boil Pot # 1	min	14	14	17	15.28	1.5	9.93%
Temp-corrected time to boil Pot # 1	min	16	16	19	17	1.8	10.45%
Burning rate	g/min	11	12	9	11	1.2	11.10%
Thermal efficiency	%	46%	45%	43%	44.80%	1.15%	2.56%
Specific fuel consumption	g/liter	33	36	34	34	1.6	4.69%
Temp-corrected specific consumption	g/liter	37	40	38	39	1.5	3.86%
Temp-corrected specific energy cons.	kJ/liter	877	946	904	909	35.0	3.86%
Firepower	watts	4,178	4,616	3,692	4162	462.1	11.10%

3. LOW POWER (SIMMER)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Burning rate	g/min	7	6	6	6.59	0.6	9.59%
Thermal efficiency	%	31%	34%	31%	32.20%	1.50%	4.66%
Specific fuel consumption	g/liter	91	79	72	81	9.7	12.01%
Temp-corrected specific energy cons.	kJ/liter	2,140	1,851	1,691	1894	227.5	12.01%
Firepower	watts	2,862	2,496	2,390	2582	247.5	9.59%
Turn down ratio	--	1.22	1.59	1.50	1.43	0.2	13.50%

BENCHMARK VALUES (for 5L)		**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Fuel Use Benchmark Value	g	643	591	547	593	48.2	8.12%
Energy Use Benchmark Value	kJ	15,106	13,878	12,843	13942	1,132.7	8.12%

IWA PERFORMANCE METRICS	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
High Power Thermal Efficiency	%	45.4%	43.8%	44.4%	44.51%	0.80%	1.80%
Low Power Specific Fuel Consumption	MJ/(min·L)	0.048	0.041	0.038	0.042	0.01	12.01%

IWA PERFORMANCE TIERS	**Tier**
High Power Thermal Efficiency	3
Low Power Specific Fuel Consumption	1

The water boiling test calculation for firewood is shown as

WATER BOILING TEST - VERSION 4.2.3	**TEST #**
All cells are linked to data worksheets, no entries are required	
Stove type/model	
Location	IOE Pulchowk Campus,Stove Testing Lab
Fuel description	Average Hardwood
Wind conditions	No wind; No wind; No wind;
Ambient temperature	18ºC; 24ºC; 24ºC; ºC; ºC; ºC; ºC; ºC; ºC; ºC

1. HIGH POWER TEST (COLD START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time to boil Pot # 1	min	16	20	25	20.31	4.2	20.5%
Temp-corrected time to boil Pot # 1	min	16	22	28	22	5.7	26.3%
Burning rate	g/min	17	12	11	13	3.2	24.2%
Thermal efficiency	%	40%	39%	35%	37.98%	2.61%	6.9%
Specific fuel consumption	g/liter	56	48	54	52.86	4.1	7.7%
Temp-corrected specific consumption	g/liter	56	53	60	56	4.0	7.1%
Temp-corrected specific energy cons.	kJ/liter	1,022	967	1,113	1034	73.6	7.1%
Firepower	watts	5,105	3,626	3,278	4003.18	970.1	24.2%

2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time to boil Pot # 1	min	15	17	19	17.06	1.7	10.12%
Temp-corrected time to boil Pot # 1	min	17	19	22	19	2.5	13.09%
Burning rate	g/min	18	14	14	15	2.1	13.82%
Thermal efficiency	%	38%	39%	32%	36.15%	3.52%	9.73%
Specific fuel consumption	g/liter	59	50	55	54.58	4.5	8.23%
Temp-corrected specific consumption	g/liter	64	56	64	61	4.7	7.67%
Temp-corrected specific energy cons.	kJ/liter	1,174	1,025	1,176	1125	86.3	7.67%
Firepower	watts	5,398	4,266	4,303	4656	643.2	13.82%

3. LOW POWER (SIMMER)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Burning rate	g/min	9	9	9	9	0.1	1.36%
Thermal efficiency	%	26%	30%	29%	28.60%	2.25%	7.87%
Specific fuel consumption	g/liter	113	110	111	111.32	1.7	1.53%
Temp-corrected specific energy cons.	kJ/liter	2,080	2,017	2,053	2050	31.4	1.53%
Firepower	watts	2,850	2,779	2,840	2823	38.3	1.36%
Turn down ratio	--	1.79	1.30	1.15	1.42	0.3	23.50%

BENCHMARK VALUES (for 5L)		**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Fuel Use Benchmark Value	g	863	818	868	850	27.4	3.23%
Energy Use Benchmark Value	kJ	15,887	15,067	15,988	15647	505.0	3.23%

IWA PERFORMANCE METRICS	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
High Power Thermal Efficiency	%	38.8%	38.8%	33.6%	37.07%	3.01%	8.11%
Low Power Specific Fuel Consumption	MJ/(min·L)	0.046	0.045	0.046	0.046	0.00	1.53%

IWA PERFORMANCE TIERS	**Tier**
High Power Thermal Efficiency	3
Low Power Specific Fuel Consumption	1

NA = Not Applicable; IWA Performance Tiers are not reported if there are fewer than 3 tests conducted.

The calculation for water boiling test for Wood Pellet is shown as

WATER BOILING TEST - VERSION 4.2.3	**TEST #**
All cells are linked to data worksheets, no entries are required	
Stove type/model	
Location	IOE Pulchowk Campus,Stove Testing Lab
Fuel description	Wood Pellet
Wind conditions	No wind; No wind; No wind;
Ambient temperature	25ºC; 24ºC; 24ºC; ºC; ºC; ºC; ºC; ºC; ºC; ºC

1. HIGH POWER TEST (COLD START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time to boil Pot # 1	min	13	20	21	17.94	3.9	21.7%
Temp-corrected time to boil Pot # 1	min	15	22	23	20	4.1	20.8%
Burning rate	g/min	17	13	10	13	3.5	26.9%
Thermal efficiency	%	40%	37%	47%	41.14%	5.19%	12.6%
Specific fuel consumption	g/liter	46	50	41	45.68	4.7	10.3%
Temp-corrected specific consumption	g/liter	51	56	45	51	6.0	11.8%
Temp-corrected specific energy cons.	kJ/liter	941	1,039	820	933	109.7	11.8%
Firepower	watts	5,084	3,856	2,955	3965.004	1,068.5	26.9%

2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time to boil Pot # 1	min	13	18	17	16.14	2.9	17.85%
Temp-corrected time to boil Pot # 1	min	15	21	19	19	3.3	17.72%
Burning rate	g/min	18	14	12	15	3.3	22.37%
Thermal efficiency	%	39%	40%	45%	41.38%	3.20%	7.73%
Specific fuel consumption	g/liter	49	56	42	48.94	7.1	14.53%
Temp-corrected specific consumption	g/liter	57	65	47	56	8.6	15.25%
Temp-corrected specific energy cons.	kJ/liter	1,044	1,189	873	1035	157.9	15.25%
Firepower	watts	5,545	4,296	3,568	4469	999.9	22.37%

3. LOW POWER (SIMMER)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Burning rate	g/min	6	7	7	7	0.8	10.95%
Thermal efficiency	%	30%	28%	30%	29.63%	1.23%	4.15%
Specific fuel consumption	g/liter	66	88	83	78.85	11.2	14.25%
Temp-corrected specific energy cons.	kJ/liter	1,218	1,612	1,526	1452	207.0	14.25%
Firepower	watts	1,850	2,280	2,213	2114	231.5	10.95%
Turn down ratio	--	2.75	1.69	1.34	1.92	0.7	38.18%

BENCHMARK VALUES (for 5L)		**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Fuel Use Benchmark Value	g	600	740	644	662	71.5	10.81%
Energy Use Benchmark Value	kJ	11,052	13,629	11,864	12182	1,317.3	10.81%

IWA PERFORMANCE METRICS	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
High Power Thermal Efficiency	%	39.2%	38.6%	46.0%	41.26%	4.09%	9.90%
Low Power Specific Fuel Consumption	MJ/(min·L)	0.027	0.036	0.034	0.032	0.00	14.25%

IWA PERFORMANCE TIERS	**Tier**
High Power Thermal Efficiency	3
Low Power Specific Fuel Consumption	2

The marginal abetment cost for Five different ICS is

Net present Values						
	TCS	ICS 1	ICS 2	ICS 3	ICS 4	ICS 5
Total cost of stove	1,248.69	6,954.91	15,218.91	3,359.45	6,266.75	6,266.75
Cost of fuel	38,123.44	10,553.92	8,122.74	19,164.67	10,143.09	10,214.81
GHG emissions	9.51	2.92	2.24	5.28	2.80	2.82
Cost of carbon						
Cost of carbon	660	NPR per ton				
		Benefit	Benefit	Benefit	Benefit	Benefit
Total cost of stove		5,706.22	13,970.22	2,110.77	5,018.07	5,018.07
Cost of fuel		27,569.52	30,000.70	18,958.77	27,980.35	27,908.63
Carbon cost		4,352.18	4,795.72	2,789.54	4,427.24	4,413.60
Total		31,921.70	34,796.43	21,748.31	32,407.59	32,322.23
Cookstove		ICS 1	ICS 2	ICS 3	ICS 4	ICS 5
Net Benefit		26,215.48	20,826.21	19,637.54	27,389.53	27,304.16
Benefit Cost Ratio		4.59	1.49	9.30	5.46	5.44
Type of cookstove		ICS 1	ICS 2	ICS 3	ICS 4	ICS 5
Marginal Abatement Cost		865	1,923	499	748	750

The Marginal abetment cost of ICS 4 for different fuel is

Net present Values				
	TCS	Charcoal	Firewood	Wood Pellet
Total cost of stove	1,248.69	6,266.75	6,266.75	6,766.75
Cost of fuel	53,372.82	42,215.70	26,372.04	40,997.75
GHG emissions	9.51	2.92	2.80	2.57
Cost of carbon	660	NPR per ton		
		Benefit	Benefit	Benefit
Total cost of stove		5,018.07	5,018.07	5,518.07
Cost of fuel		11,157.12	27,000.78	12,375.07
Carbon cost		4,352.18	4,427.24	4,580.28
Total		15,509.30	31,428.02	16,955.35
Type of cookstove		Charcoal	Firewood	Wood Pellet
Net Benefit		10,491.24	26,409.96	11,437.28
B-C Ratio		2.09	5.26	3.07
Type of cookstove		Charcoal	Firewood	Wood Pellet
Marginal Abatement Cost		761	748	795

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Date: November 26, 2023

To Whom It May Concern:

This is to certify that the paper titled "***Performance Evaluation and Optimization of Rocket Stoves for Improved Cooking Efficiency and Reduced Emission***" (Submission# **425**) submitted by **Rajan Bhusal** as the first author has been accepted after the peer-review process for presentation in the 14th IOE Graduate Conference being held during Nov 29 to Dec 1, 2023. Kindly note that the publication of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon the author's presence for presentation during the conference and timely response to further edits during the publication process.

Bhim Kumar Dahal, PhD
Convener,
14th IOE Graduate Conference

A Comparative Study of Different Improved Cooking Stoves in Nepal: Assessing Fuel Diversity Efficiency and Marginal Abatement Costs

ORIGINALITY REPORT

13%
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