ADVANCING HEATING SERVICES BEYOND THE LAST MILE

Central Asia Pilot Experience with High-Efficiency, Low-Emissions Heating Technologies
CONTENTS

ACKNOWLEDGMENTS .................................................. v
ACRONYMS AND ABBREVIATIONS ............................... vii
EXECUTIVE SUMMARY ........................................... ix

SECTION 1. INTRODUCTION ............................................. 1
  The Context ..................................................... 1
  Meeting the Heating Aspirations of the Poor ..................... 2
  Past Misperceptions ............................................. 3
  Shifting the Paradigm ............................................ 3
  Purpose and Organization of This Report ......................... 4

SECTION 2. APPLYING SCIENTIFIC UNDERSTANDING AND INDUSTRIAL DESIGN PRINCIPLES TO SMALL-SCALE COAL COMBUSTION ......... 5
  How Does Raw Coal Burn Controllably? ......................... 5
  Key Conditions for Small-Scale Coal Gasification ............... 6

SECTION 3. FROM THEORY TO PRACTICE ......................... 9

SECTION 4. FIELD RESULTS FROM THE KYRGYZSTAN PILOT ........ 11

SECTION 5. CONTEXTUALIZED DESIGN AND PRODUCTION ........ 15
  Understanding a Region’s Universe of Needs .................... 15
  Embodying Local Context ...................................... 16
  Embedding Technology in the Local Economy .................... 17

SECTION 6. EVOLUTION OF CROSSDRAFT COMBUSTOR HEATING STOVES ... 19

SECTION 7. CONCLUSION ............................................ 23
  What Has Been Learned ........................................ 23
  Moving Forward ................................................. 24
REFERENCES AND ADDITIONAL RESOURCES ................................................. 25

ANNEX A. EVOLUTION OF THE KG4 MODEL SPACING HEATING STOVE. .... 26

ANNEX B. ARTISAN DRAWINGS OF THE KG4 MODEL. ............................ 33

TABLES

BES.1.1 Performance Comparisons ............................................................... x
B1.1.1 Performance Comparisons ................................................................. 2
4.1 Comparison of Selected Respiratory Symptoms before and after KG4 Model Installations .......... 13
4.2 Comparison of Selected Respiratory Symptoms before and after KG5 Model Installations .......... 14

FIGURES

BES.1.1 Traditional Mongolian Heating Stove (left photo) and KG4 Crossdraft Gasifier (right photo) ........ x
B1.1.1 Traditional Mongolian Heating Stove (left photo) and KG4 Crossdraft Gasifier (right photo) ...... 2
2.1 Fire Chamber and Fuel Hopper. ................................................................. 8
3.1 Coke Bed below the Fire Chamber. ............................................................ 9
3.2 High-Temperature Lining Options ............................................................ 9
4.1 Household in Osh District, Kyrgyzstan ...................................................... 11
B4.1.1 Household in Uchbay Village, Osh/Nookat ........................................... 12
B4.2.1 KG4 Stove Top with Water Containers ............................................... 12
4.2 Reduced Personal Exposure to PM2.5 after KG4 Installation, Osh and Jalalabad along the CASA Corridor ................................................................. 13
5.1 Elderly Lady and Her Stove ................................................................. 15
B5.2.1 Artisan Welder ................................................................. 17
5.2 CNC Router Making a Cast-Iron Pattern for the Top Deck ..................................... 17
6.1 Crossdraft Stove Model Highlights, 2016–18 ............................................. 20
6.2 Emissions Profile: Traditional Mongolian Coal-Fired Heating Stove, 2010 ............................ 21
6.3 Emissions Profile: GTZ7.4 Crossdraft Combustor Heating Stove, 2010 ......................... 21
6.4 Performance: KG4 Crossdraft Combustor Heating Stove, 2018 .............................. 22
A.1 Sunrise in Ulaanbaatar, December 2007 .................................................. 26
A.2 G2-2000 ................................................................................................. 27
A.3 Downdraft Coal Burner ................................................................. 27
A.4 J Stove Features. ................................................................. 28
A.5 Secondary Air Injection. ................................................................. 28
A.6 Downdraft Heating Stove ................................................................. 28
A.7 GTZ7 First Prototype ................................................................. 28
A.8 GTZ7.1 ................................................................. 29
A.9 GTZ7.1 Thermograph ................................................................. 29
A.10 Cutaway Drawing of Crossdraft Combustion, 2011 ...................................... 29
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.11</td>
<td>Reconceptualized Ger Stove</td>
<td>29</td>
</tr>
<tr>
<td>A.12</td>
<td>TJ4 Prototype, Muminabad</td>
<td>30</td>
</tr>
<tr>
<td>A.13</td>
<td>Two Views of the TJ4 Model: Cooking Surface (left photo) and Ash Drawer (right photo)</td>
<td>30</td>
</tr>
<tr>
<td>A.14</td>
<td>TJ4 Performance Testing</td>
<td>31</td>
</tr>
<tr>
<td>A.15</td>
<td>MN4.1</td>
<td>31</td>
</tr>
<tr>
<td>A.16</td>
<td>MN4 Plastic Refractory Mixing (left photo) and Removing the Form (right photo)</td>
<td>31</td>
</tr>
<tr>
<td>A.17</td>
<td>W. Treter 2018</td>
<td>32</td>
</tr>
<tr>
<td>A.18</td>
<td>S. Seregin 2019</td>
<td>32</td>
</tr>
<tr>
<td>B.1</td>
<td>Welded Steel Grate</td>
<td>34</td>
</tr>
<tr>
<td>B.2</td>
<td>Cast-Iron Grate, Version 1.4, Part 1</td>
<td>34</td>
</tr>
<tr>
<td>B.3</td>
<td>Cast-Iron Grate, Version 1.4, Part 2 with Links to STL File and Pattern Maker’s STL File</td>
<td>35</td>
</tr>
<tr>
<td>B.4</td>
<td>Flat Sheet Metal Top + Bent Sheet Metal Top</td>
<td>35</td>
</tr>
<tr>
<td>B.5</td>
<td>Cast-Iron Bridge for 40 mm Side Bricks</td>
<td>36</td>
</tr>
<tr>
<td>B.6</td>
<td>Bricks, 2D and 3D Views</td>
<td>36</td>
</tr>
<tr>
<td>B.7</td>
<td>Side View of Installed Bricks</td>
<td>37</td>
</tr>
<tr>
<td>B.8</td>
<td>Rotation of Hopper Cover to Clear Smoke or See Fuel Level</td>
<td>37</td>
</tr>
<tr>
<td>B.9</td>
<td>Photos and Drawings Highlighting the KG4 Production Process</td>
<td>38</td>
</tr>
</tbody>
</table>

## BOXES

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES.1</td>
<td>Comparing Traditional Mongolian Stove and KG4 Crossdraft Gasifier</td>
<td>x</td>
</tr>
<tr>
<td>1.1</td>
<td>Comparing Traditional Mongolian Stove and KG4 Crossdraft Gasifier</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>Clarification of Key Terms and Concepts</td>
<td>6</td>
</tr>
<tr>
<td>4.1</td>
<td>Where There is Fire, Is There Always Smoke?</td>
<td>12</td>
</tr>
<tr>
<td>4.2</td>
<td>Elevating the Social Status of Low-Income Families</td>
<td>12</td>
</tr>
<tr>
<td>5.1</td>
<td>Adapting the Tajik Heating Stove Model for Kyrgyzstan</td>
<td>16</td>
</tr>
<tr>
<td>5.2</td>
<td>Local Context: A Practical Observation</td>
<td>17</td>
</tr>
<tr>
<td>A.1</td>
<td>Dispelling the Myth of Coal-Inherent Smoke</td>
<td>27</td>
</tr>
</tbody>
</table>
This technical report is produced under the Advisory Services and Analytics (ASA) project, Clean and Efficient Heating in Kyrgyzstan and Tajikistan, which aims to scale up household access to clean and efficiency heating in Tajikistan and Kyrgyzstan through building local capacity, promoting learning and collaboration, and supporting investment operations. The technical report documents the Central Asia pilot experience with high-efficiency, low-emissions (HELE) heating technologies and their potential use as a cost-effective, intermediate solution for millions of underserved households for improving health and reducing household air pollution, energy poverty, and climate impacts.

The World Bank team for the ASA project is led by Yabei Zhang and includes Kathrin Hofer, Takhmina Mukhamedova, Crispin Pemberton-Pigott, Robert van der Plas, Katharina Gassner, Yun Wu, Zamin Chargynov, and Akylai Osmonalieva. The project has built on and benefited from the development of the HELE heating technologies, which took nearly a decade of international collaboration with iterative field evaluations by researchers, designers, practitioners, and stove users in Mongolia, China, Kyrgyzstan, Tajikistan, and South Africa supported by World Bank programs and partner organizations. The World Bank–supported programs have included the East Asia and Pacific (EAP) Clean Stove Initiative (CSI), the Kyrgyzstan Efficient Heating Technologies Project, Tajikistan Winter Energy Program, Clean and Efficient Heating in Kyrgyzstan and Tajikistan Project, China Hebei Air Pollution Prevention and Control Program, and the Ulaanbaatar Clean Air Project. Key partner organizations have included the China Agricultural University (CAU) College of Engineering under the Ministry of Agriculture’s Key Laboratory of Clean Production and Utilization of Renewable Energy (China); Camp Alatoo (Kyrgyzstan); Caritas Switzerland (Tajikistan); the Climatology Research Group in North-West University’s School of Geo and Spatial Science, Potchefstroom Campus (South Africa); the Stove Emissions and Efficiency Testing (SEET) Laboratory in Ulaanbaatar (Mongolia); and the German Organisation for Technical Cooperation (GTZ, now GIZ).

The World Bank team has benefited particularly from constructive exchanges and discussions with country delegations from China, Mongolia, Kyrgyzstan, and Tajikistan, who participated in the South-South Knowledge Exchange Event organized in April 2017 to learn about and exchange information on clean and efficient heating solutions. The World Bank team is grateful for the collaboration with the European Union–funded Fresh Air Program, which provided an independent evaluation of indoor air quality and the health impacts of the HELE heating technologies pilot in Kyrgyzstan. The Fresh Air program is coordinated by Frederik van Gemert, and the Kyrgyzstan pilot evaluation was led by Talant Sooronbaev, Chief Pulmonologist of the Ministry of Health, Kyrgyz Republic.
This technical report is authored by Crispin Pemberton-Pigott, Yabei Zhang, and Norma Adams. The team is grateful for the constructive feedback provided by peer reviewers Gailius Draugelis, Yuriy Myroshnychenko, and Harold Annegarn (North-West University, South Africa). Yekbun Gurgoz from Climate and Clean Air Coalition also kindly provided review inputs. The team appreciates the valuable overall guidance provided by World Bank management and technical inputs and support by colleagues throughout the process, particularly Lilia Burunciuc, Ranjit Lamech, Jean-Michel Happi, Sameer Shukla, Rohit Khanna, Jas Singh, Abdulaziz Faghi, Husam Mohamed Beides, and Dung Kim Le.

This ASA project and publication of this technical report would not have been possible without financial and technical support provided by the Energy Sector Management Assistance Program (ESMAP). A global knowledge and technical assistance program administered by the World Bank, ESMAP assists low- and middle-income countries to increase their know-how and institutional capacity to achieve environmentally sustainable energy solutions for poverty reduction and economic growth. ESMAP is funded by Australia, Austria, Canada, Denmark, the European Commission, Finland, France, Germany, Iceland, Italy, Japan, Lithuania, Luxemburg, the Netherlands, Norway, the Rockefeller Foundation, Sweden, Switzerland, the United Kingdom, and the World Bank.
ACRONYMS AND ABBREVIATIONS

ADB  Asian Development Bank
BC   Black Carbon
BLDD Bottom-Lit Down-Draft
CAU  China Agricultural University
CI   Confidence Interval
CO   Carbon Monoxide
CSI  Clean Stove Initiative
EA   Excess Air
GIZ  German Corporation for International Cooperation GmbH (formerly GTZ)
GTZ  German Organisation for Technical Cooperation (now GIZ)
HAP  Household Air Pollution
HELE High Efficiency, Low Emissions
H₂  Molecular Hydrogen
H₂S Hydrogen Sulfide
IAP  Indoor Air Pollution
LPB  Low-Pressure Boiler (in this context, sized for individual home heating)
LPG  Liquefied Petroleum Gas
NGO  Nongovernmental Organization
NWU  North-West University (Potchefstroom Campus, South Africa)
PAH  Polycyclic Aromatic Hydrocarbon
PIC  Product of Incomplete Combustion
PM   Particulate Matter
SEET Stove Emissions and Efficiency Testing (Laboratory), Ulaanbaatar
SeTAR Sustainable Energy Technology and Research (Centre), University of Johannesburg
VOC  Volatile Organic Compound
EXECUTIVE SUMMARY

In cold-climate regions of developing countries, access to a reliable and affordable heat supply is critical to the well-being of the rural and peri-urban poor, who enjoy only limited access to district heating, natural gas, and electricity networks. At present, chronic underheating is commonplace, with negative health impacts, including illness, complications of existing medical conditions, and even death. In many cold-climate regions of Central Asia, where suppressed demand for heating energy is significant, many householders cannot afford to keep their homes warm enough to avoid adverse health consequences. In Kyrgyzstan—one of Central Asia’s poorest countries—district heating is provided to just 17 percent of the country’s 1.1 million households, mainly in the capital city of Bishkek and other major urban centers.

Most of rural and peri-urban poor in developing countries have long relied on solid fuel–fired, traditional heating stoves or simple low-pressure boilers (LPBs), which are fuel-inefficient, leaky, and highly polluting both indoors and outside. For example, traditional heating systems in Kyrgyzstan and Tajikistan are usually fueled by raw coal or various forms of dung and wood, with a thermal efficiency in a range of only 20–40 percent under normal operating conditions. Incomplete combustion and energy inefficiency contribute to energy poverty, aggravating the consequences of being chronically underheated. Smoke leaks cause household air pollution (HAP) with direct links to adverse health and climate impacts. Under a business-as-usual scenario, the continued negative implications for the national and household economy, public health, climate, and society are significant.

Having access to high-efficiency, low-emissions (HELE) heating stoves offers under-served households a cost-effective, intermediate solution until fuel-switching to gas or electricity is possible. Recent World Bank–supported winter heating pilot programs in the Central Asian countries of Tajikistan and Kyrgyzstan brought to market a small number of advanced, solid fuel–fired space heating and cooking stoves. One example is a crossdraft, coal-gasifier space heating stove called the KG4. This HELE heating stove and its LPB analogue, the KG5, were installed in 41 homes as part of the efficient heating pilot program in Kyrgyzstan the during 2016–17 winter season, with funding provided by the World Bank’s Energy Sector Management Assistance Program (ESMAP). Under this pilot, the KG4 and KG5 heating systems were manufactured by local artisans and factories in Bishkek. Further product evolution and field testing continued throughout the 2017–18 winter heating season.

This technical report aims to document the Central Asia pilot experience with HELE heating technologies and their potential use as a cost-effective, intermediate solution for millions of underserved households for improving health and reducing household air pollution, energy poverty, and climate impacts. Using the KG4 crossdraft, coal-gasifier space heating stove as an example, this report focuses on the technical aspects of the
HELE heating stove technologies, including theory, design, and field experience to help stove practitioners, project developers, and policy makers better understand why and how the HELE heating stove technologies were developed and the positive impacts they can bring.

The KG4 crossdraft gasifier well exceeded the performance of traditional stoves typical of the region. The KG4 was laboratory tested at China Agricultural University (CAU) in Beijing to quantify the PM$_{2.5}$ and carbon monoxide (CO) emissions and to establish the thermal efficiency in typical use. The performance compares favorably with a common baseline traditional heating stove. Tests showed the KG4 has a thermal efficiency 87 percent, compared to the baseline efficiency of 30 percent. Per megajoule of heat energy delivered to the home, PM$_{2.5}$ emissions are reduced by 99 percent, CO emissions by 92 percent, and black carbon (BC) emissions by 92 percent (box ES.1).

The KG4 model has found broad acceptance among Kyrgyz households participating in the winter pilot. Compared with traditional coal-burning heaters, the KG4 stove can, in theory, reduce coal consumption by 60 percent. The survey of pilot households showed that, in practice, users partition the 60 percent savings generated by the increased efficiency into reduced fuel purchases (about 40 percent) and maintaining a consistently higher room temperature, or heating more rooms of the home (about 20 percent). One-hundred percent of users reported satisfaction with the KG4 stove’s performance, with noted improvements in comfort,

### BOX ES.1 Comparing Traditional Mongolian Stove and KG4 Crossdraft Gasifier

In the winter heating season of 2016–17, the KG4 crossdraft coal-gasifier heating stove was field-tested as part of the Kyrgyzstan winter pilot, with concurrent laboratory testing in China. The KG4’s overall field performance compared quite favorably with that of the well-studied baseline traditional Mongolian heating stove (figure BES.1.1). The KG4 showed an improvement of more than 57 percent in thermal efficiency (from just under 30 percent to 87 percent) and dramatic emissions reductions (99 percent for PM$_{2.5}$ and 92 percent each for CO and BC) (table BES.1.1).

### FIGURE BES.1.1 Traditional Mongolian Heating Stove (left photo) and KG4 Crossdraft Gasifier (right photo)

### TABLE BES.1.1 Performance Comparisons

<table>
<thead>
<tr>
<th>Factor</th>
<th>Traditional Mongolian stove*</th>
<th>KG4 crossdraft gasifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal efficiency (%)</td>
<td>30</td>
<td>87</td>
</tr>
<tr>
<td>PM$<em>{2.5}$ (mg/MJ$</em>{het}$)</td>
<td>794</td>
<td>2.3</td>
</tr>
<tr>
<td>CO (g/MJ$_{het}$)</td>
<td>16.6</td>
<td>1.4</td>
</tr>
<tr>
<td>PM$_{2.5}$ reduction (%)</td>
<td>Baseline</td>
<td>99.7</td>
</tr>
<tr>
<td>CO reduction (%)</td>
<td>Baseline</td>
<td>92.0</td>
</tr>
<tr>
<td>BC reduction (%)</td>
<td>Baseline</td>
<td>92.0</td>
</tr>
</tbody>
</table>

*The well-characterized, traditional Mongolian heating stove is used as the baseline stove because the traditional Kyrgyzstan heating stoves are similar in construction, operation, leakage, emissions, and efficiency. The China Agricultural University’s BEST laboratory attempted to quantify the emissions from the traditional Kyrgyzstan heating stoves; but they were so high that they clogged the equipment and the tests had to be abandoned after two hours.
fuel savings (40 percent or higher), convenience of use, and indoor air quality. An independent evaluation by the European Union–funded Fresh Air Program showed that indoor air quality improved significantly, with a decrease in personal exposure of up to 60 percent in PM$_{2.5}$ concentrations and a dramatic reduction in respiratory symptoms for all family members.

Empirical evidence from the pilot program demonstrates that solid fuel with a known composition can be burned quite efficiently with low emissions if matched with an appropriate HELE stove architecture. A common misperception about solid fuel–fired stoves is that smoke is inherent in the fuel and therefore only by improving thermal efficiency (i.e., reducing fuel consumption) can smoke emissions be reduced proportionally. In fact, for many of the so-called improved stoves, emissions are not reduced per unit of heat delivered because the smoke is not produced by the fuel or stove alone, but by their poorly functioning combination. Furthermore, most emissions are produced during the ignition and refueling stages. Recent pilot experience demonstrates that, by applying advanced combustion science and understanding the fuel composition and broad patterns of use (i.e., the cultural context), locally produced HELE solid fuel–fired heating products can be brought to market.

The development of a small-scale, advanced combustion technology acceptable to the identified low-income rural communities was the result of nearly a decade of international collaboration and field evaluations by similarly motivated researchers, designers, practitioners, and stove users in Mongolia, China, Kyrgyzstan, Tajikistan, and South Africa. The KG4 model was informed by earlier prototypes developed in Tajikistan and modified to suit Kyrgyzstan’s colder climate, local cooking requirements, and available materials. Positive user feedback was received during the 2016–17 winter pilot; users particularly appreciated the cleaner indoor air and extended time between refueling episodes. Ongoing piloting, including intensive laboratory testing, fine-tuned variations of these HELE products. The open-source design has enabled interested stakeholders to adopt and modify the technology to fit a variety of country and cultural contexts. The combustion system developed for the KG4 model published in the open-source design site was also adapted into new designs of LPBs and other HELE heating stoves by practitioners in Mongolia, South Africa, Russia, and Poland.

Successful design and adaptation of HELE stove technologies require intensive engagement with users, stimulation of the industrial sector, and technical assistance for targeted producers. The first priority is to understand stove users’ needs, preferences, living conditions, and operating capabilities, along with the availability of equipment and properties of fuels. It is also vital to stimulate a virtuous cycle of product development, test marketing, formal market expansion, and cost reduction in the industrial sector. In the case of Kyrgyzstan, larger producers were attracted to learn the technology once they understood the potential market and, through demonstrations, how well the products worked. The open-source design approach and capacity building provided through the technical assistance grant enabled local producers to manufacture the HELE stoves. Central Asia has the potential to develop a thriving market of locally produced HELE stoves that are affordable and culturally acceptable to the intended customers. Once policy makers understand what is technically possible, incentives or regulations can be used to push for higher-performance products than current market offerings, which could lead to transformative changes for households, communities, and rural energy more generally.

This pilot experience in Central Asia shows that HELE heating stove technologies could be a cost-effective interim heating solution for the majority of poor households—mostly in rural areas—who will have limited access to viable fuel-switching alternatives (district heating network, gas, or electricity) in the short-to-medium term. By emphasizing technological innovation in the context of local culture and needs,
and strengthening local manufacturing capability and production capacity, the public sector could help build an enabling environment for market development for HELE heating stoves. It is estimated that at least 500 million people or 100 million households rely on traditional heating stoves with solid fuel (mainly coal); most of these households are located in rural areas beyond reach of the district heating or gas networks and are unlikely to be reached by these networks in the short-to-medium term. If these currently underserved households can switch from traditional heating devices to HELE heating stove technologies, the fuel savings, emissions reductions, and health benefits will be substantial.\(^1\)

\(^1\) Assuming an average household currently uses 2.5 tons of coal each year for heating, switching to the HELE technologies will provide fuel savings of 40 percent and PM\(_{2.5}\) and black carbon (BC) reductions of over 90 percent and over 85 percent, respectively. Such a switch will reduce annual emissions by 2.7 tons for CO\(_2\), 20.5 kg for PM\(_{2.5}\), and 4.7 kg for BC. Switching 100 million households to the HELE technologies would mean annual reductions of 272 million tons of CO\(_2\), 2 million tons of PM\(_{2.5}\), and 0.46 million tons of BC. One should note that the above assumptions have taken a conservative approach and assumed an average baseline technology better than what was observed in the Central Asia region (box ES.1).
THE CONTEXT

High-latitude countries with a continental climate usually experience a long winter, requiring households to use space heating appliances continuously for months. In the cold-climate regions of developing countries, having access to reliable and affordable home heating is especially critical to the well-being of low-income rural families, who typically enjoy only limited access to electricity, natural gas networks, and other sources of modern heating energy. Many cold-climate households are experiencing a suppressed demand for heating energy due to poverty and/or lack of access to modern energy infrastructure. Chronic underheating of homes, which has adverse health impacts even leading to death, is commonplace.

In many countries of Central Asia, the majority of rural and peri-urban households lack access to district heating systems or gas distribution networks. The capacity of the deteriorating electricity network is strained, and increasing electricity use to meet recurrent power shortages for winter heating is not a viable alternative. Furthermore, renewable energy sources are not yet financially viable for space heating applications at the household level, and woody biomass resources are limited. In Kyrgyzstan, district heating is limited to 17 percent of the country’s 1.1 million households, located mainly in major urban centers. To meet their space heating needs, the other 83 percent of the population—comprising mainly the rural poor—have long relied on solid fuel–fired traditional stoves or simple low-pressure boilers (LPBs) feeding radiators. If affordable, some homes supplement their stoves with subsidized electricity, often during the night. Traditional heating stoves, which burn raw coal or various forms of dung and wood, are highly polluting with typical thermal efficiencies of 20–40 percent (low power versus high power). Combustion and fuel inefficiencies contribute to energy poverty, ambient and indoor air pollution (IAP), climate impacts, and adverse IAP-linked health effects with the consequences of family members being chronically or episodically cold. Many householders cannot currently afford, or do not have the technologies needed, to keep their homes consistently warm enough to avoid negative health effects.

---

2 For an explanation of the concept, see Felicity Spors, “Suppressed Demand: Definition and Consideration of Different Approaches to Address It in CDM Methodologies,” PowerPoint presentation at the UNFCCC Standardisation Workshop, June (http://cdm.unfccc.int/methodologiesWorkshops/cdm_standards/s3_wb.pdf).

3 A multi-country study by Gasparrini et al. (2015), which analyzed more than 74.2 million deaths for various periods between 1985 and 2012, found that, for temperature-related mortality, underheating outranks heat waves as a cause of death by a large factor (ranging from 8:1 in Canada to 16:1 in China).

4 Replacing traditional coal- and wood-fired stoves and LPBs with more efficient models with a minimum thermal efficiency of 70 percent could cut household heating fuel costs in half for the same heating service or increase the mean indoor temperature at no additional fuel expense. In the villages above Osh, the reported financial benefit of the KG4 stove was US$1.40 per night.
Advancing Heating Services Beyond the Last Mile: Central Asia Pilot Experience with High-Efficiency, Low-Emissions Heating Technologies

MEETING THE HEATING ASPIRATIONS OF THE POOR

For those households unlikely to have access to modern fuels for space heating in the foreseeable future, having access to a high-efficiency, low-emissions (HELE) heating stove could be a cost-effective, intermediate solution that could rapidly be made available, at scale, until fuel-switching is possible. Recent World Bank–supported pilot programs in Central Asia have brought to market a small number of advanced, solid fuel–fired space heating and cooking stoves (World Bank 2017b). One recently field-tested stove is a crossdraft coal gasifier called the KG4, an open-source design from an international expert, with social inputs from CAMP Alatoo, a local nongovernmental organization (NGO) partner. The KG4 was manufactured by artisans and factories in Bishkek, Kyrgyzstan’s capital city (box 1.1).

BOX 1.1 Comparing Traditional Mongolian Stove and KG4 Crossdraft Gasifier

In the winter heating season of 2016–17, the KG4 crossdraft coal-gasifier heating stove was field-tested as part of the Kyrgyzstan winter pilot, with concurrent laboratory testing in China. The KG4’s overall field performance compared quite favorably with that of the well-studied baseline traditional Mongolian heating stove (figure B1.1.1). The KG4 showed an improvement of more than 57 percent in thermal efficiency (from just under 30 percent to 87 percent) and dramatic emissions reductions (99 percent for PM2.5 and 92 percent each for CO and BC) (table B1.1.1).

The KG4 adds a fuel hopper to the side of the combustion chamber (figure B1.1.1). Fuel is not added to the fire, but always to the hopper, usually twice per day instead of every 3–4 hours as occurs with traditional stoves. Below the hopper, fuel is roasted slowly to produce combustible gases, which burn quite well. A hand-operated door controls the air supply, giving the user significant control over the heating and power from 3 to 13 kW. The response to a change in the air supply is a rapid change in heating power. The heated top surface can accommodate three 3-liter pots of water, while the cooking holes accommodate cooking vessels up to 15 liters. The square hopper cover is used to warm washing water.

TABLE B1.1.1 Performance Comparisons

<table>
<thead>
<tr>
<th>Factor</th>
<th>Traditional Mongolian stove</th>
<th>KG4 crossdraft gasifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal efficiency (%)</td>
<td>30</td>
<td>87</td>
</tr>
<tr>
<td>PM2.5 (mg/MJnet)</td>
<td>794</td>
<td>2.3</td>
</tr>
<tr>
<td>CO (g/MJnet)</td>
<td>16.6</td>
<td>1.4</td>
</tr>
<tr>
<td>PM2.5 reduction (%)</td>
<td>Baseline</td>
<td>99.7</td>
</tr>
<tr>
<td>CO reduction (%)</td>
<td>Baseline</td>
<td>92.0</td>
</tr>
<tr>
<td>BC reduction (%)</td>
<td>Baseline</td>
<td>92.0</td>
</tr>
</tbody>
</table>

*The well-characterized, traditional Mongolian heating stove is used as the baseline stove because the traditional Kyrgyzstan heating stoves are similar in construction, operation, leakage, emissions, and efficiency. The China Agricultural University’s BEST laboratory attempted to quantify the emissions from the traditional Kyrgyzstan heating stoves; but they were so high that they clogged the equipment and the tests had to be abandoned after two hours.
At the beginning of the 2016–17 winter heating season, the World Bank–supported efficient heating pilot program in Kyrgyzstan installed the KG4 stove and its low pressure boiler (LPB) analogue, the KG5, in 41 rural homes. Indoor air quality, user opinions, home temperature, and fuel consumption were monitored. Field measurements showed that the kitchen’s minimum temperature was higher by an average of 5 °C.

PAST MISPERCEPTIONS

Two decades ago, the general thinking behind most improved stove programs was that fuels create smoke emissions, rather than the cause being the architecture of the device in which they were burned. That is, smoke was assumed to be inherent in the fuel. In the case of coal, common misperceptions were that switching from raw to processed semi-cooked coal or reducing coal consumption through an improvement in thermal efficiency would automatically result in reduced emissions. Observations and testing in 2007–2012 in Ulaanbaatar showed that, compared with a traditional stove, most of the so-called improved stoves did not consistently reduce emissions per unit of heat delivered. Sometimes they made the emissions worse. The reason for this is that the smoke is not actually produced by the fuel or stove alone, but by the combustion of a particular fuel in a particular stove operated in a particular fashion. Smoke is generated when the stove and fuel are mismatched, and often worst during ignition and refueling. Empirical evidence from recent World Bank–supported pilot programs in Kyrgyzstan, Tajikistan, China, Mongolia, and Indonesia shows that, with an appropriate matching of the solid fuel and HELE stove architecture, it is possible to create an efficient, solid fuel–burning stove with low PM$_{2.5}$ emissions.

SHIFTING THE PARADIGM

The development of a small-scale, advanced combustion technology broadly acceptable to low-income homeowners in Central Asia took nearly a decade of international collaboration with iterative field evaluations by researchers, designers, practitioners and stove users in Mongolia, China, Kyrgyzstan, Tajikistan, and South Africa (Annex A), assisted by years of observation and product trials in China and Mongolia. In 2010, a low-smoke coal combustor for high-volatiles coal (lignite) was developed in Mongolia by GTZ (now GIZ). This combustor was later adapted into a low-cost, brick-lined model in Tajikistan, called the TJ4. This model was successfully evolved into heating stoves appreciated by users for their convenience of operation, cooking power, controllability, and consistent delivery of heat while using much less fuel. Because comfort and convenience are subjective, the stoves had to be adapted to local climatic conditions and cultural preferences. Also, the materials, skills, and tools available in each locale had to be considered so that the stoves were “makeable.”

---

5 A smaller number were installed in rural Tajikistan in a similar pilot running in parallel.
6 Indoor air quality and 48-hour personal exposure to PM$_{2.5}$ were measured by the Fresh Air program, which also conducted detailed assessments of respiratory and non-respiratory health impacts, including lung function.
7 World Bank–supported programs have included the East Asia and Pacific (EAP) Clean Stove Initiative (CSI), the Kyrgyzstan Efficient Heating Technologies Project, Tajikistan Winter Energy Program, Efficient Heating in Kyrgyzstan and Tajikistan Project, China Hebei Air Pollution Prevention and Control Program, and the Ulaanbaatar Clean Air Project. Key partner organizations have included the China Agricultural University (CAU) College of Engineering under the Ministry of Agriculture’s Key Laboratory of Clean Production and Utilization of Renewable Energy (China); CAOMP Alatoo (Kyrgyzstan); Caritas Switzerland (Tajikistan); the Climatology Research Group in North-West University’s School of Geo and Spatial Science, Potchefstroom Campus (South Africa); the Stove Emissions and Efficiency Testing (SEET) Laboratory in Ulaanbaatar (Mongolia); and the German Organisation for Technical Cooperation (GTZ, now GIZ).
Field-testing of the locally adapted KG4 through the winter heating seasons in Kyrgyzstan (2016–17 and 2017–18) showed that numerous socioeconomic, cultural, and climate-related factors must be considered in order to successfully match users’ needs with the design fundamentals of HELE combustion. It demonstrated that it is achievable: The science of advanced combustion and efficiency can be adapted to a defined cultural context using the production skills and materials available in the local market.

**PURPOSE AND ORGANIZATION OF THIS REPORT**

This technical report aims to document the Central Asia pilot experience with HELE heating technologies and their potential use as a cost-effective, intermediate solution for millions of underserved households for improving health and reducing household air pollution, energy poverty, and climate impacts. Using the KG4 crossdraft, coal-gasifier space heating stove as an example, the report focuses on the technical aspects of the HELE heating stove technologies, including theory, design, and field experience to help stove practitioners, project developers, and policy makers better understand how and why the HELE heating stove technologies were developed. Section 2 presents the combustion theory behind the HELE stove technologies using the field-tested version of the KG4 as an example, and Section 3 explains how this theory was put into practice. Section 4 describes the results of field-testing in Kyrgyzstan, while Section 5 explains how designers can meet the manifold challenges of localization. Section 6 provides examples of advanced stove models and illustrates the lab-testing performance. Finally, Section 7 summarizes lessons learned and offers suggestions on ways to reach a large portion of underserved populations.
That solid fuels cannot be burned with low emissions in a domestic setting is a widespread misperception with potentially dire consequences for households dependent on coal, wood, or dung as a space heating fuel. It is true that some coals and woods containing toxic elements should not be used as domestic fuels in untreated form; however, poor combustion is not a fuel property. The conflation of incidental emissions from incomplete combustion with inherent emissions is a conceptual error. Seeing a “smoky” coal or wood stove does not mean that the fuel contains inherently unburnable smoke. Rather, it refers to the incomplete combustion that results from using a traditional poor-performance stove, often in combination with a mismatched fuel. By applying modern design principles and materials, advanced high-efficiency, low-emissions (HELE) heating stoves can create the appropriate combustion conditions for raw coal so that the smoke generated during the initial devolatilization, consisting mainly of condensed hydrocarbon volatiles (box 2.1), in theory, can be completely burned.

**HOW DOES RAW COAL BURN CONTROLLABLY?**

For raw coal to be burned completely, it is necessary to create gases from it and keep them hot enough, for long enough, and well-mixed with adequate air so the oxidation process (burning) is completed. It requires an appropriate balance between time, temperature, and turbulence, and these three parameters vary by fuel. Heating power can be regulated by changing the fuel-feed rate or the primary air-flow rate, both of which might be varied manually or automatically. To achieve turn-down, the fuel-feed rate could be reduced or metered, constraining the amount of heat produced. Alternatively, a full load of fuel can be maintained in the chamber, with the quantity of air flowing into it regulated or metered. These two methods, fuel metering and air metering, differ fundamentally, but, in both cases, the fuel burn rate is controlled. The KG4 crossdraft gasifier uses air metering, having a full fuel chamber and a tightly-managed air supply, capable of delivering a high space-heating efficiency across the full range of heating power.

---

KEY CONDITIONS FOR SMALL-SCALE COAL GASIFICATION

Developing a modern, domestic-scale coal gasification device requires meeting a number of essential pre-conditions. The first requirement is a mix of appropriately-sized (15–30 mm) coal, or for a single size, a fuel particle mass of 1 g per kW of anticipated firepower. In a high-performance stove, the level of excess air (EA) should be 70–110 percent (box 2.1), implying an oxygen level of 8–11 percent in the exhaust. The larger the device, the lower the permissible

BOX 2.1 Clarification of Key Terms and Concepts

In this technical report, the following combustion theory terms and technical concepts apply:

**Black Carbon (BC)**—A component of fine particulate matter (PM ≤ 2.5 µm in aerodynamic diameter) consisting of pure carbon in several linked forms. It is formed through the incomplete combustion of fossil fuels, biofuel, and biomass.

**Carbon monoxide (CO)**—A gas resulting from the incomplete combustion of carbon, which in ideal conditions is fully oxidized to produce carbon dioxide (CO₂).

**Coal properties**—Vary by source and especially age; high-quality combustion depends on tuning (i) certain dimensions of the combustor to the fuel properties and (ii) the fuel particle size to the type of combustion process.

**Coke**—Heated coal that has been pyrolyzed, leaving a hot, burning lump consisting nearly entirely of carbon and ash; all coal converts into coke before becoming ash.

**Combustion efficiency**—The extent (percentage) to which the fuel components are burned to completion. Restricting air flow to an ideal value creates a very hot fire, which can burn the hydrocarbon fuel constituents completely, leaving only CO₂ and water vapor; however, if the air supply is inadequate, combustion quality deteriorates rapidly, possibly creating thick smoke. Properly regulating the excess air makes the fire hot and combustion complete.

**Draft**—The negative pressure (measured in Pascals) in a chimney created by the gases inside being hotter than the surrounding air; this pressure difference (buoyancy) drives air into the stove and pulls the exhaust gases out.

**Excess air (EA)**—Percentage of air supplied to the combustion chamber in excess of what is theoretically required for stoichiometric combustion (i.e., the exact amount of oxygen needed to combine with the carbon and hydrogen in the fuel to produce CO₂ and H₂O). EA is reported as a percentage of the amount of air actually needed. The EA level provides one of the most useful metrics for combustion analysis. The higher the EA, the lower the heating efficiency.

**Heat delivered**—Heat energy transferred from the stove to the living space expressed as a percentage of the heat available. For a natural draft stove (no fan), some of the heat energy is required to create draft in the chimney as the driving force to move air through the stove. The minimum heat required to maintain the chimney draft is approximately 10 percent of the total available, leaving a maximum of 90 percent potentially available for space heating. National standards frequently require a thermal efficiency of 70 percent or greater.

**Heating versus cooking stoves**—Cooking stoves cook food and heat water. Heating stoves heat homes and (usually) heat water. In Kyrgyzstan, all three functions are basic requirements for nearly all homes. A cooking stove system can be socially complex, while space heating is mainly an engineering problem.

**Heating wall**—Vertical, hollow brick wall to which the stove is connected, used to extract and store heat from the exhaust.

**Local context**—The combination of fuels and operator preferences for cooking and water heating, plus the pot-holding capacity, cooking height, ash management, and service standard for heating (e.g., 1,000 degree-days per month).

---

10 For small-scale, low-tech biomass stoves, the ideal gasification conditions for a similarly effective combustor have not yet been developed. Because of the large amount of oxygen contained in biomass (40 percent by weight), the ideal percentage range for excess air, fuel size, and general stove construction will differ from a coal stove.
Section 2: Applying Scientific Understanding and Industrial Design Principles to Small-Scale Coal Combustion

EA. High-volatiles coal provides for easy ignition and also requires less kindling wood (i.e., 400 g instead of the traditional 1,500 g).

During the gasification process, there will be no flaming combustion in the gasification zone. The combustion-zone temperature must be sustained above ~830 °C to ensure combustion of the carbon monoxide (CO) (box 2.1). The fire should be constrained within a round or rectangular channel, not a large open space; and the grate should be able to drop the ash without agitation.11

---

Localization—Production of the design by local artisans and/or factories using whatever materials and equipment they have at their disposal; this is the local context from the producer’s perspective.

PM$_{2.5}$—Particulate matter (smoke) with an aerodynamic diameter less than 2.5 microns; in general, solid fuel–fired stoves do not emit many particles larger than 1.5 microns, most being smaller than PM$_{1.0}$. The metric used for rating the smoke emissions of a stove is the mass of PM$_{2.5}$ in milligrams per megajoules of heat delivered into the home or cooking pot, expressed as PM$_{2.5}$, mg/MJNET.

Pyrolyzation—The thermal decomposition of fuel; heating a solid fuel drives off volatile compounds in the form of gases and evaporated liquids during the initial fuel-heating stage. All solid fuels initially undergo thermal decomposition when placed in the fire chamber.

Refractory materials—Those materials designed to be used at high temperature (e.g., as the lining of a combustion chamber or the pyrolysis zone).

Semi-coke—Coal that is largely pyrolyzed on the outside that may contain some volatiles inside. Charcoal is semi-coked biomass. All coal placed in a fire is first dried and then semi-coked, coked, and finally burned until the only solid material remaining is ash, comprising entirely mineral matter and no carbon-containing components.

Smoke—Fine particles of solid and liquid semi-volatile material suspended in air. These condensed-phase particles are composed almost entirely of unburned fuel. Coal smoke consists mainly of condensed liquid or tar droplets of various hydrocarbons with a small amount of wet or dry carbon while fuel is pyrolyzing, plus black carbon after it has been coked. Smoke is not produced if a fire is hot enough and ventilated correctly so as to burn all of the evolved gases and particles to completion. Polycyclic aromatic hydrocarbons (PAHs), products of incomplete combustion (PICs), PM$_{2.5}$, and volatile organic compounds (VOCs) are not inherent in the fuel; they result from poor combustion in sub-optimal conditions.

Soot—Dry, black particles comprising predominantly carbon and tar, formed during incomplete combustion of the fuel.

Volatile organic compound (VOC)—A subset of volatiles; any toxic, carbon-based (organic) substance with a high vapor pressure at ordinary room temperature.

Thermal efficiency—The quantity of heat delivered into the home, expressed as a percentage of the heat energy of the fuel fed into the stove. In this report, the denominator is calculated on a Lower Heating Value (LHV) basis.

Volatile—Those components of coal that can be evaporated if the coal is heated to 400 °C in the absence of oxygen; the portion that cannot be evaporated is largely fixed carbon and the rest is inert, mineral ash. Coal composition is typically reported in three mass fractions: volatiles, fixed carbon, and ash.

---

11 Coals with “weak” ash (e.g., Kyrgyz Kara-Keche or Mongolian Nalaikh) are preferred as they de-ash the grate without intervention. Shenmu coal from Shanxi, China is another example.
A fuel hopper, located immediately above the upper end of the grate, feeds new fuel into the gasification process; it must ensure that the active volume on the combustion chamber is continuously refilled with fuel in order to sustain pyrolysis (box 2.1), all the while maintaining a nearly-constant volume of coke on the lower part of the grate. In addition, the heat-exchanger bypass must be adequate to ensure the chimney is kept warm enough to create, by draft, adequate negative pressure within the stove at all times. Finally, the stove body, ash drawer, and any other openings must maintain a close-fitting, almost air-tight seal.

The hopper-fed crossdraft combustor is characterized as having six zones corresponding to the steps involved in the fuel distillation, cracking, and combustion processes (figure 2.1). After appropriately-sized raw coal fuel is loaded in the hopper (zone 1) and the hopper cover is sealed, dehydration and devolatilization commence (zone 2). Next, semicoking of the coal begins, which generates a large quantity of thick smoke (zone 3). During gasification (zone 4), smoke is “cracked” into simple gases within a bed of hot coke. The resulting coal gas is burned with secondary air in the gas combustion area (zone 5), sometimes referred to as the fire chamber. Finally, heat is transferred to the room via the heat exchanger or the cooking pot (zone 6). As long as fuel is available in the hopper and the ash is cleared, these gasification processes can continue indefinitely. Depending on the ash properties, the fuel may feed down by gravity alone, while unattended, for 4–14 hours at a time, depending on the burn rate and, to a lesser extent, the fuel properties.

If the physical characteristics of the fuel, grate, and the fuel depth on the lower grate are well-chosen, then gravity alone will feed appropriately-sized coal into the combustion zone without user intervention. This self-feeding function is extremely important to householders because, in practice, the hopper can be filled, the power level set, and the stove left unattended for several hours. Under conditions observed in rural Kyrgyz homes, 10 kg of fuel permits the stove to burn for 14 hours (lowest power) or 4 hours (high power). Coals with stronger ash or high ash content can be burned effectively, but the grate must be shaken periodically (every 2–6 hours), depending on the power level and the physical characteristics of the ash.

A minimum level of chimney draft – approximately −20 Pascals measured at the top of the fire chamber – is required to make this combustor burn with very low smoke emissions. At this level of draft (or more), the turbulent air-gas mixing is adequate, and ideal conditions can be maintained. To achieve this, the vertical chimney should be at least 4.1 m tall (measured from the stove top) for adequate draft, and a gas temperature of 160 °C in the chimney 2.4 m above the floor should be maintained when operated at high power.
The KG4 coal stove prototypes use the coal gasification processes described in the previous section. Gently heating a minimum of about 4 kg of coal drives off the volatiles. This creates thick smoke within the coal bed, composed of long-chain hydrocarbon polymers and other gases (e.g., \( \text{C}_x\text{H}_y\text{O}_z \), \( \text{CH}_4 \), \( \text{CO} \), and \( \text{H}_2 \)), which move through the hot coke on the lower grate at the base of the fire chamber. Once all the moisture and volatiles have been driven off, what remains are hot, glowing pieces of coke (figure 3.1). The grate is angled so that a small pile of 900 °C coke is maintained under the combustion chamber at all times. All gases produced by heating the coal pass through that coke. This sedate process allows enough time for the complex distilled volatiles (\( \text{C}_x\text{H}_y\text{O}_z \)) to undergo thermal decomposition into simpler gases: \( \text{CH}_4 \), \( \text{CO} \), \( \text{H}_2 \), and \( \text{H}_2\text{O} \). The combustible gases burn with a translucent yellowish flame (figure 3.1).

Because the fire is hot and confined within the chamber, the metal stove body requires protection in the form of a refractory ceramic lining. The science of refractory ceramics has advanced greatly in the past few years. High-performance phosphate-bonded materials have great merit as they can be made without firing parts in a kiln. Stove producers can hand-form the parts using simple molds and hand or electric mixing. Such materials as aluminum dihydrogen phosphate and aluminum orthophosphate bonded alumina or geopolymers made from industrial waste and coal ash are promising because they allow for small-scale production without a large investment in tooling or having to formulate exotic fired-clay materials. For the Kyrgyzstan efficient heating pilot program, locally made refractory bricks were used. A program in Mongolia uses a cold-setting, phosphate bonded “plastic refractory” material that resembles cement when dry (figure 3.2).
Computer-controlled plasma and laser cutting of steel plate are available in major centers, making it possible to conduct field trials of localized versions of stove designs adapted to local pots and fuels. These cutting machines allow for the production of hundreds of identical parts at reasonable cost. In the Kyrgyzstan efficient heating pilot program, multiple producers made the stoves, but all parts were cut by one supplier to guarantee dimensional accuracy and, ultimately, performance of the final product.
During the winter heating season of 2016–17, the KG4 coal-gasifier stove, along with its low-pressure boiler (LPB) analogue, the KG5, were field-tested in 41 rural and peri-urban homes in Kyrgyzstan. Hands-on instructions in the use and maintenance of the stoves and fuel preparation were provided. Most of the coal used was from Kara-Keche. User surveys, conducted by CAMP Alatoo, the pilot program’s local nongovernmental organization (NGO) partner, occurred 10 weeks after installation and again later in the heating season.

Results of the user surveys showed that the KG4 stoves were broadly accepted by pilot participants (World Bank 2017a). These households reported a range of benefits in terms of improved home comfort and convenience of use, savings in fuel expenditure, and better health. All pilot participants agreed that their homes were consistently warm and more comfortable after installing the new stoves. The majority reported that they used about 40 percent less fuel compared with the previous winter season, even though they heated their homes continuously and had a more comfortable temperature. Survey respondents indicated that, in most homes, additional rooms (10–30 percent of the house area) could be heated with the new stove because it produced more heat, while using significantly less fuel (figure 4.1). It was reported that the winter sleeping area, typically a room connected to the kitchen by an open doorway, was much warmer than before the KG4 installation. About 90 percent of users reported spending less time starting and refueling the fire; in addition, more than 80 percent perceived a reduction in smoke leakage, with the additional reported benefit of not having to repaint the kitchen walls every few months (boxes 4.1 and 4.2).

Concurrent with the 2016–17 winter pilot, a Fresh Air program,12 implemented by the International Primary Care Respiratory Group (IPCRG), measured 48-hour personal exposure to PM$_{2.5}$ (from all sources) for those householders responsible for cooking (in most cases a woman). The control group for personal exposure consisted of 20 homes that did not switch to the new stoves. For the 41 pilot participant households (the treatment group), Fresh Air’s

---

12 https://www.theipcrg.org/freshair
IPCRG team took personal exposure measurements two months after stove installation and again one year later, in the winter of 2017–18. The results showed that the KG4 model improved indoor air quality significantly. In 2016–17, PM$_{2.5}$ concentrations for the baseline control group averaged 153 µg per m$^3$. Two months later, PM$_{2.5}$ concentrations had fallen to an average of 83 µg per m$^3$ for the treatment group. By the winter of 2017–18, this average had further declined to 61 µg per m$^3$ (figure 4.2).

Improved indoor air quality and reduced personal exposure to PM$_{2.5}$, in turn, had a positive impact on the respiratory symptoms of household members. After KG4 installation, coughing, wheezing, and breathing difficulty (dyspnea) disappeared for most children and adults in the participating households (tables 4.1 and 4.2). Following installations
in Chui District, incidence of chest infections among children in the 11 participant households fell from 86 percent to 13 percent, and incidence of children with more than two chest infections fell to just 1 percent, a remarkable 31 points below the baseline incidence.\(^\text{13}\)

With better health, children-days absent from school decreased significantly, household members made fewer visits to clinics, and they had reduced medical expenses. The reduction in HAP was mainly attributable to (i) the far fewer ignitions required by the KG4 stove during the winter heating season (in some cases, the stove was ignited only once), (ii) the large reduction in gas/smoke leaked into the home, and (iii) a correctly sized and effective chimney installation.

\[\text{FIGURE 4.2 Reduced Personal Exposure to PM}_{2.5}\text{ after KG4 Installation, Osh and Jalalabad along the CASA Corridor}\]

\[\text{TABLE 4.1 Comparison of Selected Respiratory Symptoms before and after KG4 Model Installations}\]

<table>
<thead>
<tr>
<th>Metric</th>
<th>Before installation (%)</th>
<th>After installation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coughing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults</td>
<td>50.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Children</td>
<td>32.8</td>
<td>0</td>
</tr>
<tr>
<td>Wheezing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults</td>
<td>10.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Children</td>
<td>7.7</td>
<td>0</td>
</tr>
<tr>
<td>Dyspnea</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults</td>
<td>40.0</td>
<td>0</td>
</tr>
<tr>
<td>Children</td>
<td>53.6</td>
<td>4.4</td>
</tr>
</tbody>
</table>

\[\text{Note: Participant households included 30 homes in Osh and Jalalabad Districts, along the CASA Corridor.}\]

\[\text{Frederik van Gemert, Fresh Air Program Coordinator, the Netherlands, stated that, after installation of the KG4 and KG5 stoves, “... symptoms almost all disappeared, the number of chest infections were reduced drastically, and missed school days by children were lowered tremendously. The people were impressed by the new heaters/stoves, particularly Model 4, and fully accepted [them].”}\]
### TABLE 4.2 Comparison of Selected Respiratory Symptoms before and after KG5 Model Installations

<table>
<thead>
<tr>
<th>Metric</th>
<th>Before installation (%)</th>
<th>After installation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coughing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults</td>
<td>71.4</td>
<td>0</td>
</tr>
<tr>
<td>Children</td>
<td>53.8</td>
<td>0</td>
</tr>
<tr>
<td><strong>Wheezeing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults</td>
<td>35.7</td>
<td>8.3</td>
</tr>
<tr>
<td>Children</td>
<td>7.7</td>
<td>0</td>
</tr>
<tr>
<td><strong>Dyspnea</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adults</td>
<td>57.1</td>
<td>0</td>
</tr>
<tr>
<td>Children</td>
<td>69.2</td>
<td>0</td>
</tr>
</tbody>
</table>

*Note: During the 2016–17 winter pilot, the KG5, an analogue LPB version of the KG4, was field-tested in participant households that had water-heated radiators with proportionally similar results. Participant households included 11 homes in Chui District.*
To effectively meet the challenge of localization, heating stove designers must first appreciate the household consumer’s needs and perceptions, aspirations, and realities. What is the condition of the residence? What seasonal weather must the household endure? How many degree-days of heating are required? A range of factors influence the perceptions of potential stove users. Key among their concerns are the ability to heat multiple pots of water, adequate cooking power and control, social status of the fuel used, and pride of ownership. Other considerations include fuel flexibility, attention demand to tend the stove, ease of cleaning, and ability to maintain a comfortable temperature (figure 5.1).

Stove designers for the Kyrgyzstan efficient heating pilot recognized that there are multiple sources of HAP. Even when a model produced a large drop in PM$_{2.5}$ emissions in the testing laboratory, it was understood that user operations might depart from what had been observed or modeled, and there would inevitably be a point of diminishing returns on performance for added costs. For these reasons, typical local fuel quality was an important input for the design, while the optimum fuel particle size was an output. The chemical and physical analyses of available coals were checked, and new models were fine-tuned to accommodate the fuels households were likely to use. It happens that the required size (16–25 mm) is cheaper than the most common choice (80 mm), saving up to 33 percent per kg. This saving is additional to the economic benefit of the lower fuel consumption.

**UNDERSTANDING A REGION’S UNIVERSE OF NEEDS**

The winter heating requirements of a cold-climate region are not limited to individual households. During the initial market survey for the parallel Tajikistan winter heating pilot, six heating applications were identified: (i) clinics, (ii) schools, (iii) pre-schools (which are warmer), (iv) home heating, (v) home heating plus cooking, and (vi) individual units heating in multi-story apartment buildings. The ability to warm water was required of all the...
selected models even when cooking was not needed. The heating of public buildings was limited to daytime hours, i.e., the appropriate high-efficiency, low-emissions (HELE) stove would be ignited on a daily basis and operate without attention. The Tajikistan Model 4 was one of six products developed to address these particular heating needs.

The KG4 was adapted from the Tajik TJ4.0 and was sized to heat 50–70 m² homes in regions where winter temperatures can fall to −30 °C, (e.g., the Pamir region and Kyrgyz highlands). Based on feedback from producers, consumers, installers, and project leaders, an updated version of the TJ4.0, designated KG4, was adapted to each pilot region’s available materials, producer skills, and performance requirements (box 5.1). These requirements vary by altitude, cooking culture, fuel type, and traditional patterns of behavior. Great care was taken to engage with producers about consumers’ preferences, concerns, and their level of acceptance and enthusiasm for the new stoves.

**EMBODYING LOCAL CONTEXT**

Stove designers and producers face unique challenges in embodying the local context. Designers must make the stove “makeable,” since brilliant designs are of little value if workshops cannot build them. The challenge is to retain all of the functions of the ideal prototype, while adapting it to on-the-ground realities, including locally available materials, tools, and skills. Production is possible at two scales: (i) approved artisans assembling parts cut by an approved supplier and (ii) any approved formal-sector factories with the ability to arrange everything in-house (box 5.2).

For the Kyrgyzstan pilot program, all sheet-metal parts were made using a CNC plasma-cutting contractor to ensure reliable dimensions and thus performance. Producers without this machine had two options. They could

---

**BOX 5.1 Adapting the Tajik Heating Stove Model for Kyrgyzstan**

By late 2016, the TJ4.0 model had performed quite well using refractory bricks in a metal shell. KG4 adaptations focused on accommodating pots and tuning the combustion air supply, the heat-exchanger size (not too big), and most importantly, the distance between the bottom of the central dividing wall and the angled grate passing beneath it. This gap (height of block 3, figure 2.1) controls how fuel falls from the hopper and is dictated by the wall thickness and coal characteristics. It sets the coke-bed depth, which, in turn, sets the level of excess air in the fire above.

For each coal type, the dimensions of the combustion chamber and the grate bar spacing were determined by trial, error, calculation, and re-trial. The resulting architecture was highly efficient, had low emissions and was, to a certain extent, self-feeding of the fuel. Following successful emissions and efficiency testing conducted at the China Agricultural University (CAU) in Beijing, the design was finalized and the drawings circulated to producers.

Note: The drawings are in the public domain and are available online (https://collaboration.worldbank.org/content/sites/collaboration-for-development/en/groups/clean-cooking-and-heating-solutions/files.asset.html/content/usergenerated/asl/cloud/content/sites/collaboration-for-development/en/groups/clean-cooking-and-heating-solutions/files/jcr:content/content/primary/library/space_heating_stoves-ywyV/kyrgyzstan-btpI/kg-4_3-DdYt.html).

---

14 In Kyrgyzstan, cast-iron production capacity is adequate. Producers had access to modern CNC cutting equipment for parts standardization, and welding skills in each industry-size group were relatively high.
use an “artisan” version of the drawings with small changes for operations they could perform manually. This version requires more welding but only a few tools (angle grinder, tape measure, and arc welder). Or, producers with plasma-cutting and metal-bending machines could make a bent-metal version, which required less welding. In order for producers to move from one level of production to the next, they were required to use the appropriate set of drawings and have their product samples approved by the project inspector before sale (Annex B).

**EMBEDDING TECHNOLOGY IN THE LOCAL ECONOMY**

The KG4 heating stove is considered affordable for rural and peri-urban households in Kyrgyzstan. A field visit to a mountain village near Osh District showed that households that switched from a traditional solid fuel–fired heating stove to the KG4 model enjoyed a net fuel expenditure savings of US$48 per month. At the time of the 2016–17 heating pilot, the stove featured a steel top rather than a more durable cast-iron top, and cost US$160, giving a payback period of 3.3 months.

Anticipated repairs for the KG4 are related to burning out the steel top of the stove (those made with a mild steel top) and corrosion from heat and condensation inside the heat exchanger. The expectation is that this level of repairs can be handled by any of the many artisan welding shops in Kyrgyzstan. The new cast-iron grate—a locally manufactured, owner-replaceable part—may eventually burn away. This would occur more quickly if made from a reinforcing bar. The cast-iron top is expected to last for many years.
Following the successful winter pilot of 2016–17, the World Bank continued to provide technical assistance to refine the prototypes and provide training to local producers on the design of the HELE stove technologies. A KG4.3 model with a cast-iron top and grate was piloted in the 2017–18 winter heating season. At present, at least four producers located in or near the capital city of Bishkek have demonstrated the skills needed to produce these HELE stove technologies to a satisfactory standard. Some of them have invested in additional equipment to expand their production capacity.
The evolution of crossdraft combustor heating stoves is an ongoing, empirical process. Observations over the past decade, including intensive laboratory testing, led to the creation of better-performing models that have been field-tested and adapted to a variety of country and cultural contexts (Annex A). Iterative versions of these models have adjusted dimensions of parts, used alternate assembly methods, and made adjustments for use with particular fuels. These revisions—both major and minor—have contributed to the larger changes, together resulting in high-impact performance (figure 6.1).

The testing protocol adopted and further developed during the World Bank–supported Indonesia Clean Stove Initiative (CSI) project is used to assess stove performance. It is instructive to compare the real-time emissions performance of a traditional coal-fired heating stove with that of an advanced HELE model equipped with a crossdraft coal combustor.

Figure 6.2 shows the real-time PM$_{2.5}$ emissions profile for a traditional Mongolian heating stove burning Nalaikh raw coal. The stove was produced in a typical artisan workshop. The emissions profile covers a 3.5-hour burn sequence (ignition, loading, and one refueling episode). The addition of a few kilograms of fuel at 70 minutes is a perturbation from which the stove recovers after 20 minutes. Two hours after ignition, the coal has been reduced to coke, which burns with low emissions. The major portion of emissions come during ignition and refueling.

Figure 6.3 shows the same 3.5-hour burn sequence, using the same raw coal, for the 2010 model GTZ7.4 prototype (Annex A). It is this combustion system that was used in the Kyrgyz KG4 stoves. Test results show that, compared with the baseline stove (figure 6.2), the GTZ7.4 model achieved a 99 percent reduction in PM$_{2.5}$ emissions. This confirms that the crossdraft combustion system is capable of producing a dramatic improvement in performance without

---

15 Testing was done using the CSI Heterogeneous Test Protocol, currently under the custodianship of the China Agricultural University (CAU) in Beijing. This method can be used for cooking, heating stoves, and water-heating boilers, applying a culturally-relevant test sequence.

16 The traditional Mongolian heating stove is used as a baseline here because the traditional Kyrgyzstan heating stoves are similar in construction, operation, leakage, emissions and efficiency. The CAU’s BEST Lab attempted to quantify the traditional Kyrgyzstan heating-stove emissions, but they were so high that the equipment became clogged and the tests had to be abandoned after two hours.

17 The size of the perturbation is related to the amount of fuel added. In winter, adding 10 kg to a hot stove at 10:00 p.m. creates the midnight pollution spike. Prior to 2013 with mainly old stoves, a city’s ambient air quality was poorly correlated with the mass of fuel burned, but well-correlated with the number of ignitions and refueling events.
Advancing Heating Services Beyond the Last Mile: Central Asia Pilot Experience with High Efficiency Low Emissions Heating Technologies

Recent pilot program experience in several countries of Central Asia (Mongolia, Tajikistan, and Kyrgyzstan) show that, by understanding and applying the underlying theory of coal gasification and adapting the stove design to locally available fuels, it is possible to achieve 80 percent thermal efficiency, with \( \text{PM}_{2.5} \) emissions under 3 mg per MJ\(_{\text{net}} \) (figure 6.4). This has been achieved with a minimal change in production costs to produce high-efficiency, low-emissions (HELE) heating stoves that are affordable to low-income families.
FIGURE 6.2 Emissions Profile: Traditional Mongolian Coal-Fired Heating Stove, 2010

PM 2.5 and Mass Burned 081.10.4.1

Stove Manufacturer: Ulaanbaatar
Stove Model: Traditional stove, traditional fire

FIGURE 6.3 Emissions Profile: GTZ7.4 Crossdraft Combustor Heating Stove, 2010

PM 2.5 and Mass Burned 114.10.4.1

Stove Manufacturer: GTZ
Stove Model: GTZ 7.4
**FIGURE 6.4** Performance: KG4 Crossdraft Combustor Heating Stove, 2018

<table>
<thead>
<tr>
<th>Stove Manufacturer: Altynebeck</th>
<th>Test date</th>
<th>12-Apr-2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model: KG4.3</td>
<td>Type of Fuel</td>
<td>Shenmu Coal 8.85%</td>
</tr>
</tbody>
</table>

PM 2.5 and Mass Burned BST_177.10.4.1

Note:
The ash is still in the stove.
The heat value/kg considers this.
The test should end when 90% of the fuel loaded (total) has been burned.

<table>
<thead>
<tr>
<th>PM</th>
<th>CO</th>
<th>Reduction in PM2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>794 (mg per MJ)</td>
<td>16.6 (g per MJ)</td>
<td></td>
</tr>
</tbody>
</table>

Emissions per Megajoule from the fire

<table>
<thead>
<tr>
<th>PM2.5</th>
<th>CO</th>
<th>Reduction in PM2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1.2</td>
<td>= PM mass/Fire Heat</td>
</tr>
</tbody>
</table>

Emissions per Net Megajoule from the fire

<table>
<thead>
<tr>
<th>PM2.5</th>
<th>CO</th>
<th>PM2.5, Thermal Eff 86.8%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>1.4</td>
<td>99.7%</td>
</tr>
</tbody>
</table>

Emissions per MJ delivered into the home

<table>
<thead>
<tr>
<th>PM2.5</th>
<th>CO</th>
<th>CO, Thermal Eff 86.8%</th>
</tr>
</thead>
<tbody>
<tr>
<td>99.7%</td>
<td>91.5%</td>
<td></td>
</tr>
</tbody>
</table>
This technical report documents the demonstration at pilot scale of an advanced, solid-fuel combustion technology that can deliver high-quality, small-scale heating services that meet the aspirations of rural and peri-urban households who lack access to the district heating system or cannot afford modern heating fuels (e.g., electricity or gas). In the case of the Kyrgyzstan efficient heating pilot program, 100 percent of participant households with a KG4 model in the home used it for cooking in addition to space heating; 100 percent of those households also used the stove for heating water for making tea, washing, and ablutions.18

WHAT HAS BEEN LEARNED

Prioritizing User Engagement. The design and adaptation of high-performance technologies can be done successfully if it first involves an intensive engagement with users to understand the local context: their needs, preferences, living conditions, operating capabilities, and the availability of competing fuels and equipment. Apart from heating services, the cooking power, duration, and frequency must be studied and characterized.19

Stimulating the Industrial Sector. A virtuous cycle of product development, test marketing, formal market expansion, cost reduction, and quality improvements can be stimulated in the industrial sector of cold-climate developing countries. In Kyrgyzstan, prototypes were developed in partnership with informal sector welders. Larger producers were attracted to participate in the pilot only after they understood the potential market and how well the products worked, which required demonstrations to overcome the incredulity factor. To date, four large producers in or near the capital city of Bishkek have demonstrated their ability to produce HELE stoves by attending the technical training sessions and following the open-source designs.

Providing Technical Assistance for Product Design and Development. Setting high targets for emissions, combustion, and thermal efficiency can stimulate product development. In developing countries where the research and development capacity is relatively low, technical assistance in open-source product design and development is deemed essential. Partnering international experts with local experts and producers has had, and can continue to have, profound and sustained impacts on improving local capacities. In a practical sense, the projects involved on

---

18 Importantly, heating water is not considered cooking per se by the cultures in this region.
19 In the case of rural Kyrgyzstan, this stage took 1 year to complete, during which time production problems and cost issues were also addressed.
the journey (Kyrgyzstan, Tajikistan, South Africa, Mongolia, and China) are leading by example, closely working with local partners, participating in knowledge exchanges, and sharing technical advances with other project teams and countries’ stakeholders.20

MOVING FORWARD

It is estimated that at least 500 million people or 100 million households rely on traditional heating stoves with solid fuel (mainly coal); most of these households are located in rural areas beyond reach of the district heating or gas networks and are unlikely to be reached by these networks in the short-to-medium term. High-efficiency, low-emissions (HELE) heating technologies are feasible and can provide rural and peri-urban households a cost-effective, intermediate solution for access to modern heating services long before fuel switching is possible. The economic, social, climate, and air quality benefits are substantial,21 as evidenced by the independent measurement of impacts in the Central Asia pilots. It is possible to build a local market for HELE heating technologies by applying technology design and production processes that consider local culture and conditions and making the technologies accessible to users. For this to happen, external support is needed (from government or international donors) to (i) raise awareness to accelerate adoption of HELE technologies, (ii) help the poor if they cannot afford these technologies as part of social support programs, and (iii) help upgrade local producers’ skills (e.g., design assistance; bidirectional knowledge transfer; and initial investments in prototypes, testing, casting patterns, and field installations) so they can continually improve their services.

---

20 A South-South Knowledge Exchange Event held in Beijing in April 2017 brought the four countries together to learn and exchange clean and efficient heating solutions (http://www.worldbank.org/en/events/2017/04/17/clean-and-efficient-heating-south-south-knowledge-exchange-event#1).

21 Assuming an average household currently uses 2.5 tons of coal each year for heating, switching to the HELE technologies will provide fuel savings of 40 percent and PM$_{2.5}$ and black carbon (BC) reductions of over 90 percent and over 85 percent, respectively. Such a switch will reduce annual emissions by 2.7 tons for CO$_2$, 20.5 kg for PM$_{2.5}$, and 4.7 kg for BC. Switching 100 million households to the HELE technologies would mean annual reductions of 272 million tons of CO$_2$, 2 million tons of PM$_{2.5}$, and 0.46 million tons of BC. One should note that the above assumptions have taken a conservative approach and assumed an average baseline technology better than what was observed in the Central Asia region (box ES.1).
REFERENCES AND ADDITIONAL RESOURCES


The Efficient, Clean Cooking and Heating Community of Practice
https://collaboration.worldbank.org/groups/clean-cooking-and-heating-solutions
ANNEX A

EVOLUTION OF THE KG4 MODEL SPACING HEATING STOVE

This annex describes the historical development of the KG4, the latest version of the KG4.x crossdraft coal gasifier. It explains how this heating stove evolved over the past decade, including the key roles played by various organizations along the way. It demonstrates how the enabling environment for stove development was maintained long enough to deliver the high-impact results that were achieved under the recent Kyrgyzstan efficient heating pilot program.22

FIGURE A.1 Sunrise in Ulaanbaatar, December 2007

EARLY EFFORTS

In late 2007, a consultant was recruited to assist the World Bank’s Mongolian team under the Ulaanbaatar Clean Air Project to assess how to create better stoves with much lower smoke emissions within the constraints of the existing market and develop national standards that could support a sustainable transition in the manufacturing sector. At that time, domestic stove emissions were choking Ulaanbaatar—one of the world’s coldest and most air-polluted capital cities. Two years earlier, the World Bank had been assigned the key role of coordinating efforts to ameliorate Ulaanbaatar’s air pollution (figure A.1).23

Efforts to decrease emissions by improving thermal efficiency (not better combustion) had already been supported by various organizations for nearly a decade. At the time, the target was to reduce fuel consumption by 30 percent, assuming that emissions per kilogram burned would remain the same: “burn less fuel, emit less smoke.”

22 Drawings for all models of these stoves are in the public domain and are available for downloading from the following website, where they are listed by country: https://collaboration.worldbank.org/content/sites/collaboration-for-development/en/groups/clean-cooking-and-heating-solutions/files.asset.html/content/usergenerated/asi/cloud/content/sites/collaboration-for-development/en/groups/clean-cooking-and-heating-solutions/files/jcr:content/content/primary/library/space_heating_stoves-ywyv/kyrgyzstan-btpi.html

23 Alarm 4 (Blue): heavy air pollution the next day (201–300 µg per m³), Alarm 3 (Yellow): serious air pollution the next day (301–500 µg per m³) or heavy air pollution for the next three days, Alarm 2 (Orange): heavy or serious air pollution alternatively in the next three days, Alarm 1 (Red): serious air pollution for the next three days.
The assumption that the fuel could not burn well was a mistake. Worse, a poor family, burning an average of 4.5 tons of winter fuel each year, still felt cold. A stove that delivered more heat per kilogram of coal was certainly welcome, but this did not necessarily mean it would burn less fuel. The big improvement had to come from improving the combustion system, plus a thermal efficiency bonus.

One of the “improved stoves” supported in 2007 was the GTZ G2-2000 (figure A.2). It was a 110 kg brick-lined metal box with a chimney, heat exchanger, small water-heating tank, and radiating fins. Although the combustion produced no less particulate matter (PM) than the traditional stove on which it was based, it did deliver about 20 percent more heat to the ger per kilogram of fuel burned.24

In late 2007, a US$30 example of a downdraft combustor was used to test the burn quality of local fuels (figure A.3).25 By type, it is a “J Stove” because the gas path is shaped like the letter J. It proved that local coals could be burned indefinitely with a combustion efficiency of 99.5 percent, emitting minimal smoke or smell even when refueled. The ease with which such high performance was achieved proved that the root cause of ambient air pollution was neither the fuel nor stove alone; rather, it stemmed from a mismatch of the stove and fuel properties (box A.1).

In the J Stove, coal is fed into the top of the big pipe, and is supported by a grate at the bottom. The flame goes down into the steel cone below, then travels around the corner and up into the chimney—the leg of the J. The chimney pulls fresh combustion air downwards into the top of the big pipe, which serves as a fuel reserve. Dimensioned correctly, there is strong turbulence in the cone, a high combustion temperature, and a low level of excess air (figure A.4). The combination yields extremely low PM emissions.

---

**BOX A.1 Dispelling the Myth of Smoke-Inherent Coal**

One may well ask why the J Stove combustor produced so little smoke when it had been assumed by most of the engaged parties that smoke was inherent in the fuel. Somewhat like putting diesel fuel into a gasoline engine, putting Nalaikh coal into a Mongolian traditional wood stove results in a tremendous loss of energy and a large amount of smoke—the smoke being evaporated, unburned, or badly burned fuel. The local fuel and the traditional stove do not work well together. If the coal is burned properly in a well-matched stove, nearly all smoke from combustion of the coal is also burned and the result is the observed high-efficiency, low-emissions (HELE) performance.

---

24 A traditional ger is a Mongolian-style yurt (portable round tent); in Ulaanbaatar city, some 600,000 people live in gers.

25 A clean downdraft, coal-burning stove had been patented in England in the late 1600s but was not widely known in Asia. According to one anecdote, one model was available in Ulaanbaatar in 1906, made by a Russian immigrant.
Having ruled out the coal as the root problem of air pollution, the search was on to find or create a workable product that produced virtually no smoke and that could meet the heating and cooking needs of more than half a million ger dwellers.

**ITERATIVE DEVELOPMENT**

By 2008, development work at the Sustainable Energy Technology and Research (SeTAR) Centre at the University of Johannesburg, South Africa showed that introducing preheated secondary air, creating a swirl in the conical combustion chamber, consistently delivered the very low-emissions level sought. The bottom-lit down-draft stove (BLDD 3) featured a hopper, secondary air pipe, and conical combustion chamber (figure A.5). In 2009, the burner was incorporated into the first stove in Ulaanbaatar (figure A.6). It could burn both semi-coked briquettes and raw coal, producing only 2 percent of the emissions typical of traditional stoves. Also, it was very quick-lighting. Although the space heating performance was superior, it was not culturally suited to local cooking requirements.

In September 2010, a parallel effort on the part of a GTZ (now GIZ) building-efficiency project in Ulaanbaatar created a small-scale version of a German-made household-scale, water-heating boiler. At that time, the Asian Development Bank (ADB) was creating the SEET stove testing laboratory, which afforded all of those involved in developing hardware a means for testing the effect of their clean stove designs. The GTZ miniaturization effort succeeded somewhat, but the stove was complex to build and difficult to ignite, even with raw coal.

The GTZ7 crossdraft stove had a good cooking-performance potential. This model featured a hopper, flat cooking surface, and a down-up heat exchanger (figure A.7). The next year, a commercially viable version, the

---

26 Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH sponsored the UJ SeTAR Centre in 2009 in order not to lose the technical capacities developed during the years of the ProBEC program in the SADC countries.

27 Semi-coked briquettes are much more difficult to ignite and require a larger minimum fire size to remain alight.
GTZ7.1 (the first of five iterations), was produced in exploratory quantities. This was a major advance in the clean combustion of low-quality coal. Under ideal conditions, PM and CO dropped to undetectable levels.

Nick-named the “Tractor,” the GTZ7.1 was designed as a modular stove (figure A.8). This version had cooking and space heating options that bolted onto a combustor with an integrated fuel hopper. Measured against a traditional stove, PM and CO were reduced by 88 percent and 85 percent, respectively. Without the heat exchanger, it could be used to heat a high-mass brick heating wall with or without the optional cooking platform.

A thermograph of a fully ignited GTZ7.1 stove shows the highly desirable radiation from the combustion zone (the bright spot), while the heat exchanger (dark box) heats air by convection; the dark circular object is a thermocouple connector housing (figure A.9). This stove was very effective at heating the living space at knee level. A ger is not effectively heated by a stove that largely generates vertical convection. Stoves must radiate significantly to heat nearby objects and people.

Figure A.10 shows how, during crossdraft combustion, black coal drops into the pyrolyzation zone, where it is dried and heated. As shown, a bed of semi-coke forms and falls down and to the right, creating a coke bed under the gas combustion zone. The coke bed cracks the long-chain volatiles (smoke) into clean-burning, combustible gases, such as CO, CH₄, and H₂. As the coke burns to completion, the ash falls through the grate. Combustion air (blue arrows) passes up through the grate and the red-hot coke, preheating the air to more than 800 °C. Cooking occurs above the fire (green pot).

In 2013, a private initiative took a completely fresh approach to designing the ger stove, imagining tool bars for various purposes hooked onto the sides, with all the same combustion principles preserved (figure A.11). Importantly, the design could be constructed using standard refractory bricks in a metal shell (i.e., without requiring specially-formed clay parts). The ends were to be cast iron and the body formed from a single sheet of bent metal.
FIELD-TESTING IN TAJIKISTAN

In 2015, the World Bank office in Tajikistan responded to the country’s increasingly difficult heating situation by supporting the development of six new stove models under a technical assistance grant, in collaboration with Caritas Switzerland. The all-brick concept from 2013 was retrieved, and a simplified proof-of-concept version was constructed using a steel and ceramic liner inserts (figure A.12). Despite its extreme simplicity, the stove’s performance was quite good, comparing favorably with that of the GTZ7 versions from five years before. The Tajik model had a metal divider, later eliminated, between the fire-chamber bricks and the hopper. It used the long chimney pipe as a heat exchanger so the gas exit temperature was high. Later versions added an air-to-air heat exchanger at the back.

The TJ4 model was field-tested in a 2016–17 winter heating pilot. The stove’s essential features were tight control of the air supply, a brick-insulated combustion chamber, a large cooking pot hole with a cover, and having the general appearance of a traditional stove (figure A.13). The main difference was that the hopper holding the coal reserve was lined with brick. The goal was to have good control and stable heating power for six hours. The burn quality was quite good. It is essential that no air enters or exits the fuel hopper cover. In this first version of the model, the ash drawer was used as a combustion air regulator, but it proved too coarse a method of control. The door was also tried as an air regulator; it was found to work, but lacked fine control. This issue was resolved by creating a separate sliding air regulator within the main door.

FIELD-TESTING IN KYRGYZSTAN

By mid-2016, under the World Bank Kyrgyzstan Efficient Heating Technologies Project, in collaboration with CAMP Alatoo, the TJ4 model was replicated in Kyrgyzstan with modifications to suit that country’s colder climate, cooking requirements, and available materials. Kyrgyzstan’s more developed industrial sector made it possible to create a more engineered product—the KG4 model—which was piloted in the 2016–17 winter heating season. In parallel, special drawings for an artisan version of the stove were created so that microenterprise welders could produce a KG4 model with the same performance (Annex B). Through the winter heating season of 2017–18, the KG4 version was field-tested with success in additional peri-urban and rural homes. Also, a low-pressure boiler (LPB) version—the KG5.0—was successfully field-tested in homes with water-heated radiators.28

28 In early 2017, the KG2.5, an uprated biomass stove derived from the Tajikistan TJ2.0 model, was field-tested in homes that burned dung and wood almost exclusively. The Tajik version proved unable to heat highland homes at −30 °C, so a larger version of KG2.5 was introduced with success. High-performance, dung-burning designs are rare.
Concurrent with the Kyrgyzstan efficient heating program, the TJ4 model was replicated in Beijing for the China Agricultural University (CAU). From mid-2016, the stove underwent extensive heating and cooking performance testing by a graduate student in CAU’s College of Engineering (figure A.14). She investigated the stove’s performance, using various types and sizes of coal and semi-coked briquettes. Of all the fuels tested, low-ranked raw Shanxi coal (16–25 mm in size) was found to burn the cleanest, emitting less than 0.5 mg PM$_{2.5}$ per MJ$_{\text{NET}}$. The stove consistently achieved full gasification of the volatile hydrocarbons.

**FURTHER DEVELOPMENT IN MONGolia**

In 2018, the KG4 version—by now referred to as the “Magic Stove” by many stove users—was replicated in Ulaanbaatar by the World Bank–supported Stove Development Center and tested in the Stove Emissions and Efficiency Testing (SEET) laboratory, long-since transferred from the ADB to the Mongolian University of Science and Technology. This Mongolian copy of the KG4, called the MN4.1 (figure A.15), was again slightly modified to suit the available materials and welding skills; preference for a larger cooking vessel; and, importantly, made with a shorter body to suit the limited space in a *ger*. Testing revealed that coal consistently overheated briefly in the hopper starting after one hour of operation. This problem was solved by ventilating the sides of the hopper and keeping the heat exchanger heat away from the hopper walls. Fundamentally, it was a return to the general structure of the GTZ7.1 with a modernized shell and materials.

The inconvenient-to-use, imported refractory firebricks were dropped in favor of a cement-like, advanced plastic refractory material with excellent results (figure A.16). Using this material eliminates the need to fire high-temperature stove components in a kiln because they are cold-setting, like epoxy. The current product is the MN4.2, which is shorter in length than the KG4, and has a distinctive heat radiation hole on each side that cools the contents of the hopper.

Today, Kyrgyz producers can replicate the MN4.2, but using their locally-made refractory bricks.

---

29 Expressions of interest in the TJ-4 model came from China, South Africa, and Mongolia through an existing stove-science cooperation agreement. Through the Ulaanbaatar Clean Air Project, the University of Johannesburg’s SeTAR Centre was cooperating closely with Mongolia on product design, particularly for downdraft stoves.
**ADAPTATION IN SOUTH AFRICA**

Meanwhile, North-West University (NWU) in Potchefstroom, South Africa is already testing a locally made TJ4; it has reproduced and tested the MN4.2 with Witbank sub-bituminous coal and downsized it to make the SA8.0. This South African version is adapted to suit the milder winters on the South African Highveld, along with local cooking preferences (e.g., flat-bottomed cooking pots and a minimum of two cooking stations) (figure A.17). A few SA8.0s were to be field-tested in low-income homes in 2018. They use a novel geopolymer refractory material in the fire chamber.

In addition, the combustion system developed for the KG4 model published in the open-source design site was also adapted into new designs of LPBs and other HELE heating stoves by practitioners in Poland (figure A.18) and Russia (figure A.19).
This annex contains selected drawings and photos of the artisan version of the KG4 (version 1.42), including the cast-iron grate, which became available in 2018 (figures B.1–B.9). Each drawing has an embedded direct link to click on for downloading (figures B.1-B.8). The full set of drawings is available in a single .dwg format file.\(^{30}\)

This version of the KG4 model was used in the winter heating season of 2017–18, and the indoor air quality measurements are relevant to it. However, it is not the latest version of this technology. Further developments in both Mongolia and South Africa in 2018 have modified the heat exchanger in order to produce a shorter and wider body to fit into the typical structures of a Mongolian ger and South African township homes. Planners might consider both this version of the KG4 (longer) and the newer MN4.2 and SA8.0 models (shorter), which can be found in this library. These drawings have been used in 2018 by practitioners to make copies of the KG4 in Poland and Russia.\(^{31}\)

\(^{30}\) [Link to file]

\(^{31}\) It was reproduced by both Wojciech Treter of czysteogrzewanie.pl and Sergei Seregin of kamicenter.ru
This can be a 7-bar or 8-bar grate, depending on the nature of the coal ash.
Annex B: Artisan Drawings of the KG4 Model

FIGURE B.3 Cast-Iron Grate, Version 1.4, Part 2 with Links to STL File and Pattern Maker’s STL File

Cast-Iron Grate, final sized 3D STL file: Same drawing as above, but links to the STL file.
Note: Pattern maker’s STL 3D file is 3 percent larger in the expectation that aluminum patterns will be made from the wooden master.

FIGURE B.4 Flat Sheet Metal Top + Bent Sheet Metal Top

Top Deck Outside dimensions

Top Deck with 40mm Lip

C Pemberton-Pigott
FIGURE B.5 Cast-Iron Bridge for 40 mm Side Bricks

Dwg. KG4.3.12.11
Model KG4.3B
Version 1.2
8 Nov 2017

BRIDGE
C Pemberton-Pigott

FIGURE B.6 Bricks, 2D and 3D Views

Dwg. KG4.3.12.13
Model KG4.3B
Version 1.2
8 Nov 2017
C Pemberton-Pigott

BRICKS 2

Brick 1
250 x 58.5 x 60

Brick 2
250 x 120 x 60

Brick 3
120 x 60 x 60

Brick 4
230 x 120 x 60

Brick 5
250 x 60 x 60

Brick 6
208 x 120 x 60

Brick 7
150 x 120 x 60

Brick 8
165 x 105 x 6
**FIGURE B.7** Side View of Installed Bricks

![Diagram showing side view of installed bricks]

**FIGURE B.8** Rotation of Hopper Cover to Clear Smoke or See Fuel Level

![Diagram showing rotation of hopper cover]

Air enters to clear smoke before refueling.

Rotate hopper cover to clear smoke or see the fuel level.
FIGURE B.9 Photos and Drawings Highlighting the KG4 Production Process

Machining the large cast-iron ring

Underside of the cast-iron hopper cover, machined flat

Cut-away set of refractory bricks in position

Full set of refractory bricks in position

Artisan’s workshop in Bishkek, Kyrgyzstan

Bricks forming the hopper (top view)

Brick-cutting with electric wet saw

Adding the handle connector to an 8-bar cast-iron grate