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Perception, culture, and science: A framework to identify in-home heating options to improve indoor air quality in the Navajo Nation

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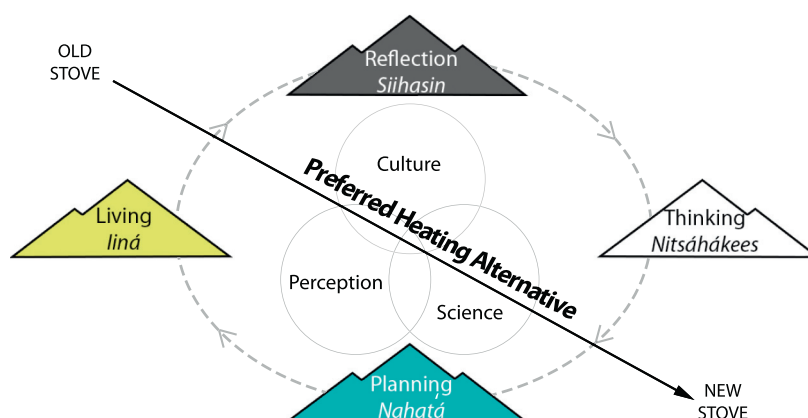
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HIGHLIGHTS

- A new framework for identifying appropriate heating alternatives for the Navajo Nation is proposed
- This framework balances reducing health and environmental impacts with Navajo culture, perception, and technical assessment
- This assessment uncovered discrepancies between community perception and the technical results
- Involvement of the Navajo Nation people at the onset and throughout a study such as this, is critical to a successful result

GRAPHICAL ABSTRACT



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ABSTRACT

A 2010 study identified higher than average incidence of respiratory disease in Shiprock, NM, the largest city in the Navajo Nation. That study suggested that the potential cause was the combustion of solid fuels in in-home heating stoves and that respiratory disease could be greatly reduced by changing indoor heating behaviors and improving heating stove quality. Since the Navajo people are deeply embedded in culture and traditions that strongly influence their daily lives, a new framework was needed to identify feasible heating alternatives that could reduce the negative environmental and health impacts related to solid fuel use while respecting the culture of the Navajo people.

The resulting Navajo framework included perception, cultural, and technical assessments to evaluate seven heating alternatives perceived viable by Navajo stakeholders. Cultural experts at the Diné Policy Institute identified potential cultural limitations and motivating factors for each alternative. A limited technical assessment of the health benefits of these options was conducted and integrated into the process. A parallel convergent mixed-methods approach was employed to integrate qualitative and quantitative results. The results and

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Wood
Health and environmental benefits

framework developed and presented here may be useful for decision makers in communities heavily reliant on solid fuels for heat, especially Native Nations, where culture plays an important role in the success of any intervention.

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1. Introduction

1.1. The Navajo Nation

The Navajo Nation (NN) is the largest sovereign Native American nation within the United States (population 175,000) (US Census Bureau, 2014a) occupying about 69,930 km² within Arizona, New Mexico, and Utah (Fig. 1). Its population is growing nearly twice as fast as the US average (Navajo Housing Authority, 2011) and 32% of the population is under six years of age (US Census Bureau, 2014b). These populations are at a higher risk of health effects from indoor air emissions (Sly and Flack, 2008). The poverty rate in the NN is 42% (US Census Bureau, 2014c) compared to the US average of 16% (US Census Bureau, 2014d), directly impacting their access to clean energy.

Dinétah (the Land of the People, in the Navajo language) is part of the Colorado Plateau at an altitude of 1680 m. There are two coal-fired power plants (points a and b in Fig. 1) within the boundaries of the NN, and five coal-fired power plants and a hydroelectric plant within 80 km of the NN border (points c–h in Fig. 1), yet 20% of Navajo homes are off the grid/lack electricity (Navajo Housing Authority, 2011).

According to the US Census Bureau (2014e), wood is the primary heating fuel in 63% of all Navajo homes, followed by electricity (12%), natural gas (11%), propane (10%), and kerosene, fuel oil, or other fuels (3%). The Navajo Housing Authority (NHA), however, reported that as many as 89% of rural Navajo homes use wood stoves for heating (NHA, 2011). While not identified in surveys by the US Census Bureau and NHA, unprocessed Black Mesa and Fruitland high-volatile bituminous coals (Kirschbaum et al., 2013), are distributed freely or at low cost and are widely used by NN residents to heat homes primarily at night (Hickmott et al., 1997; Bunnell et al., 2010).

Navajo dwellings include contemporary single family homes (59%), mobile homes (17%), multi-family attached housing (13%), and traditional *hogans* (eight sided homes with a wood burning stove and open roof in the center) (11%) (NHA, 2011). It is estimated that 63% of Navajo homes were built before 1990 (US Census Bureau, 2014f) and are probably in need of weatherization (e.g., caulking and weather stripping).

Houses built by the NHA during the 1970's and 1980's often have no attic insulation, while newer NHA homes are more likely to include this feature. Eighty percent of Navajo homes are owned by the residents (NHA, 2011); however, home improvements done by owners may not follow housing codes, including insulation requirements.

1.2. Air quality and health in Shiprock, NM

Shiprock, NM is the largest city (population 9,000) in the NN, is located near the Four Corners Power Plant, and is part of the Farmington, NM Metropolitan Area (US Census Bureau, 2014g). Farmington (population 45,900) lies 50 km east of Shiprock (Fig. 1), just outside the NN border. Average daily high temperatures in the Shiprock–Farmington area range from 24 °C in summer to −2 °C in winter; average daily lows are below −1 °C from November through March, reaching extremes as low as −37 °C (NOAA, 2011). Between 2005 and 2014, this region experienced an annual average of 139 days at or below freezing (0 °C), 18 cm of rain, and 25 cm of snow (NOAA, 2015a).

Heating Degree Days (HDD) are commonly used to assess heating demands and are defined as the difference between the daily mean ambient temperature (e.g., 30 °F) and a defined indoor comfort temperature (e.g., 65 °F). The HDD for this day (65–30) would be 35 °F and then each day's difference is summed over a time period (e.g., if all days had a difference of 35 for a 30-day month, the monthly HDD would be 35 × 30 = 1050). In the past 100 years (1915–2014), homes in the NN (New Mexico Climate, Division 1 and Arizona Climate, Division 2) have required 29% more heating than those in the contiguous U.S. annually (5912 vs. 4598 HDD) (NOAA, 2015a). During the past ten years (2005–2014), homes in Shiprock have needed 17% more heating than those in the contiguous U.S. (5064 vs. 4322 HDD annually) (NOAA, 2015b). Weatherizing Shiprock homes should reduce the energy required for heating and indoor air pollution.

Shiprock experiences low wintertime inversions that trap air pollution close to the ground, including combustion emissions from home heating (Hickmott et al., 1997). Wood and coal combustion produce a complex mixture of emissions (Gaston et al., 2016), including fine and ultrafine particulate matter (PM) (McDonald et al., 2000; Bond et al., 2002; Schurman et al., 2015), polycyclic aromatic hydrocarbons (PAHs) (Fine et al., 2004; Chen et al., 2005; Samburova et al., 2016), and carbon monoxide (CO) (Jaszczur et al., 1995; Venkataraman and Rao, 2001). These components have been associated with adverse health effects (Butt et al., 2016; Solomon et al. 2012; Breyse et al., 2013). Correlations between higher outdoor concentrations of PM_{2.5} and decreased life expectancy in the U.S. have been observed (Pope et al., 2009; Fann et al., 2012). Barone-Adesi et al. (2012) correlated higher lung cancer mortality in China with domestic use of bituminous coal, the type mined at the Black Mesa coal field (Kirschbaum et al., 2013). Similar-rank coal from the Fruitland Formation in the San Juan Basin (Kirschbaum et al., 2013) is also used by Navajo residents living near the Broken Hill Proprietary (BHP) Billiton Navajo mine (Bunnell et al., 2010), posing similar health concerns. Recently, the World Health Organization (2014) strongly discouraged any unprocessed coal use indoors.

Bunnell et al. (2010) indicated that 77% of Shiprock residents surveyed (n = 137) used an indoor stove for heating and 25% used coal in stoves not designed for that fuel. This use potentially results in increased indoor air pollution because the higher coal combustion temperatures promote cracking of the stove walls, allowing stove

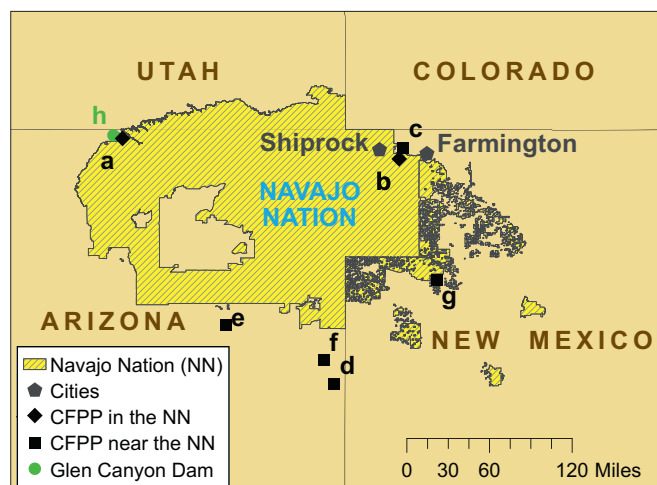


Fig. 1. Map of the Navajo Nation and four corners area (CFPP - Coal-fired Power Plants).

emissions to leak into the house (MacKay et al., 2003). Hickmott et al. (1997), in their survey, observed that many stoves used by survey respondents were inherited or fabricated by relatives and most users burned a combination of wood and coal. They also determined that local stove retailers often did not specify what fuel should be used in the stove being purchased. Bunnell et al. (2010) observed over 100 times higher 24-h average indoor concentrations of $\text{PM}_{2.5}$ ($38 \mu\text{g m}^{-3}$; $n = 19$) in Shiprock homes heated with coal during winter months compared to one home heated with propane ($0.29 \mu\text{g m}^{-3}$) during the same period, exceeding the WHO recommended guideline of $25 \mu\text{g m}^{-3}$ (World Health Organization, 2014). The study also observed three times higher indoor 24-h $\text{PM}_{2.5}$ concentrations in those homes during winter ($36 \mu\text{g m}^{-3}$; $n = 20$) compared to the summer when no coal was used ($12 \mu\text{g m}^{-3}$; $n = 8$).

Bunnell et al. (2010) also observed higher rates of hospitalization due to respiratory conditions during the winter relative to summer and Shiprock ranked in the top 10 out of 37 surrounding communities for prevalence of the seven respiratory diseases studied. Past studies have found associations between wood stove use and increased respiratory illness. A study of Navajo homes in and near Ft. Defiance, AZ indicated that among Navajo children under 2 years old, increased prevalence of acute lower respiratory infection (ALRI) was associated with wood stove use (odds ratio, $\text{OR} = 5.0$) and high ($\geq 65 \mu\text{g m}^{-3}$) 15-h average PM_{10} indoor concentration ($\text{OR} = 7.0$) (Robin et al., 1996). Morris et al. (1990) examined respiratory illness among Navajo children of the same age group and of the ten factors studied, only wood stove use and recent respiratory illness exposure were independently associated with higher risk of ALRI.

1.3. The In-home Heating Alternatives Project (IHAP)

Motivated by these previous studies, the goals of the IHAP were to assess in-home heating alternatives for residents of the Navajo Nation and provide recommendations for a stove replacement program that integrates the Navajo Nation's unique culture and perception of the alternatives with infrastructure and availability limitations and a technical analysis of the alternatives. The IHAP is also responsive to a call by the WHO to develop research on indoor solid fuel use (World Health Organization, 2014). Previously, Smith (2002) proposed that the adoption of any household device requires more than just technical and economic efforts, and relies upon social, cultural, and perceptual factors. Similarly, Heltberg (2005) identified taste of prepared meals and tradition as being more important factors than cost in fuel-switching in Guatemala. Patel et al. (2016) recognized that many market-based approaches to cook-stove intervention fail to account for critical factors including cultural structure. Troncoso et al. (2007) found that cooking with open fire was sometimes preferred in rural Mexican homes simply because it is customary. Person et al. (2012) observed that perception of neighbors and peers in rural Kenya strongly influenced the decision to purchase an improved cook-stove. None of these studies, however, proposed nor applied a methodology to integrate perception or culture on a technical solution.

Initially, the project convened stakeholders that included tribal, federal, academic, and private entities as well as NN residents and students. These stakeholders identified potential heating alternatives and established a framework for comparison that involved community members, NN cultural experts, and scientists. This community-science-based approach emphasized the integration of Navajo perception and culture with a technical analysis of heating alternatives, and may provide insight for similar issues in other communities with distinct cultural traditions.

2. Study design and methods

2.1. Diné analytical framework

Fundamental Navajo Law was integrated into this study and states that tradition is a resource for finding solutions. The Navajo are guided

by the overarching philosophy of Sà'ah Naagháí Bik'eh Hózhó (SNBH). Principles of SNBH are still relevant to modern environmental and health issues, such as those associated with indoor home heating practices within the Navajo Nation. The esoteric knowledge contained in the Navajo philosophies were provided by experts within the Diné Policy Institute and integrated into the study. Specifics and details are maintained within the Navajo culture.

2.2. Study design and implementation

This study applied a parallel convergent mixed-methods approach (Creswell et al., 2011; Creswell, 2009; Johnson et al., 2007), which consisted of three parts: 1) gauging community perception of heating alternatives identified in the stakeholder's workshop and judged by community members; 2) identifying important cultural factors relevant to each alternative; and 3) conducting a limited technical assessment of environmental and health benefits associated with each alternative. Each assessment was conducted independently and then combined using concurrent triangulation.

In Navajo belief, restoration of environmental and public health (balance; *hozho*) requires partnership, community consensus, education, and critical thinking. The first step for the Diné (Navajo) People in problem solving is thinking (*Nitsáháskées*), followed by planning (*Nahat'á*), action (*liná*), and reflection (*Siihasin*) in a continuous cycle. This study followed these concepts to investigate how to address the heating needs of the NN and reduce the potential negative health effects caused by emissions from indoor solid fuel.

2.3. Selection of heating alternatives

Seven heating alternatives were selected by the IHAP stakeholders for assessment in the study: central furnaces that use 1) natural gas (NG), 2) propane gas (PG), or 3) electricity (EH); 4) wood pellet stoves (WP); 5) improvement to an existing wood stove (SI); 6) replacement with an improved wood or wood/coal stove (SR); and 7) passive solar heating (PS). Descriptions of each heating alternative follow and they assume a properly installed and operating system.

2.3.1. Natural gas

Typically centralized units (furnaces) require utility gas and electricity for the blower as well as flue ducts and additional ductwork throughout the house. Maintenance needs include annual inspections and cleaning of the blower wheel, motor, combustion chamber, and air filter (Franklin, 2000). Individual room heaters are not available for natural gas. Furnace emissions are low and emitted outdoors.

2.3.2. Propane gas

Propane heating in this community is primarily by centralized units (selected for this assessment). Centralized propane furnaces require a large liquid propane gas (LPG) tank near the home and transfer pipe from the tank to the house. PG has similar infrastructure and maintenance requirements as NG.

2.3.3. Electrical heating

Electric heaters are of two main types: centralized units and space heaters. Centralized furnaces using blowers (selected here for analysis) have similar infrastructure and maintenance requirements as centralized gas furnaces, excluding the gas transfer line or large outdoor tank. There are no indoor emissions; however, emissions depend on the pollution controls associated with the centralized power plants that provide electricity to the area. The emissions may have an impact regionally. Space heaters heat one or two rooms.

2.3.4. Wood pellet

Most wood pellet stoves considered have combustion efficiencies between 58 and 75% (US EPA, 1996), easy and automated loading

mechanisms, and burn a waste product, such as wood, corn, or grass. Electricity is required to run the automated loading mechanism and blower, and wood pellets only may be accessible to residents in populated areas like Shiprock. Maintenance needs are similar to other wood burning devices and include annual stove and chimney cleaning (Houck and Eagle, 2006). Emissions are exhausted through a flue to the outdoors.

2.3.5. Stove improvement

Stoves used in many Shiprock homes are old and the fuel used may not be appropriate for the stove type. Many have cracked or missing stove walls and flues and thus higher emissions indoors (Bunnell et al., 2010). In this option, stoves in reasonably good condition would be repaired but not replaced. Repairs included replacing gaskets and flue with new double-walled construction. Emissions are exhausted through the flue to the outdoors.

2.3.6. Stove replacement

This option replaces old stove with non-catalytic US EPA-certified wood stoves with efficiencies of 66–73% (US EPA, 1996). Emissions are eliminated through a flue. Hickmott et al. (1997) suggested that Navajo residents are likely to continue mixed use of wood and coal due to the low cost of coal and its ability to heat the house all night long. Therefore, wood stoves should only be recommended for homes where coal will not be used. Dual wood/coal stoves are available but are not EPA certified, although EPA is in the process of evaluating and certifying dual wood/coal stoves (Stewart, 2016).

2.3.7. Passive solar

Passive solar heating uses sunlight to heat the home and does not require electricity. In this alternative, additional insulation, increased window area on the south-facing wall, and/or upgrade of existing windows would be used (NREL, 1991), alongside the continued use of an old conventional wood stove that is properly functioning. An enclosed room extension or Trombe wall also may be added to the house (Balcomb and McFarland, 1978). The Southwestern U.S. and the Colorado Plateau receive abundant solar radiation (Fig. S1) for the efficient application of passive solar heating.

2.4. Community perception assessment

As part of a course, students at Diné College designed a project and obtained voluntary and basic information from their families regarding heating alternatives and how they rated these alternatives (Perry Charley, personal communication, April 1, 2014). This class project involved data gathering and analysis as part of the student learning strategies and their understanding of community-based projects. A total of 56 community members including students, their family members, and advising faculty participated in this class exercise. The criteria were described orally to the respondents and are included in Table S1A. The resulting secondary data formed the basis for the Perception Assessment performed by the IHAP. Refined descriptions used in the final assessment are included in Table S2. The difference between the two sets of descriptions highlights the importance for employing a framework that promotes early engagement of all relevant stakeholders, clear communication among them, and creation of instruments that use local language and perceptions yet reflect accepted scientific standard methods.

Community members assigned a score to each criterion for all seven heating alternatives. The scores used were:

- 5 – 'Very feasible'
- 4 – 'Highly feasible'
- 3 – 'May be feasible'
- 2 – 'May not be feasible'
- 1 – 'Not recommended'

0 – 'Not feasible'.

A two-tailed Wilcoxon Signed-rank Test was applied to the perception data since it had a non-normal distribution. An alpha (α) value of 0.05 was used to determine if a perceived alternative was significantly different from all other alternatives for a given criterion. One-sided statements of significantly less (or least) feasible or significantly more (or most) feasible have α values of 0.025 and were derived from the two-tailed test, as recommended by the UCLA Statistical Consulting Group (2016). There were a total of 3136 perception responses (56 respondents $\times$ 7 alternatives $\times$ 8 criteria).

2.5. Cultural assessment

Diné fundamental law recognizes relationships between people, the sacred elements (land, air, water, and heat), Mother Earth, and Father Sky. Diné people understand that these entities each have rights and freedoms of their own and that the sacred elements are balanced only when natural resources are cared for (*baa aháyá*), valued (*baa háá hasin*), respected (*díłzin*), and cherished (*dóó baa ja' hóná*). The Diné Policy Institute (DPI) at Diné College, a research institute established to "mesh" Western research methods with Fundamental Navajo Law, determined cultural implications for each heating alternative by assessing its relationship with sacred elements and the preservation of balance attained through their use.

Results of this assessment were integrated into the Framework without further analysis to preserve its authenticity. In this study, its main role was to determine if strong limitations or motivations for a given alternative became apparent. A proper implementation of this Framework would emphasize a thorough cultural assessment such that a complete suite of both negative and positive cultural factors are identified.

2.6. Technical assessment

A limited Technical Assessment was conducted using available modeling tools and had three main components. First, a Typical Navajo Home was modeled using Building Energy Optimization (BeOpt) software (v 2.3) (NREL, 2013a). The house was defined to have an area of 93 m² and be located in Shiprock, NM. The home was not weatherized and had significant air infiltration from the outside (see Tables S3 and S4 for BeOpt inputs and outputs) and used an inefficient wood stove for heating. Default BeOpt home values were used except for: R-values (i.e., capacity to resist heat flow) for wall and ceiling insulation, exterior finish, shingle color, exposed floor area, and window area (Table S3). These variations in input parameters were based on personal communication with Navajo residents, as well as an unpublished Navajo home modeling effort by the US EPA (Stewart 2014, personal communication). Second, a Baseline Home was defined as a Typical Home with standard weatherization (reducing its annual average air exchange per hour, AAACH, from 0.60 to 0.40) and modeled with BeOpt to determine the reduction in heating load. Third, each heating alternative was evaluated separately using the Baseline Home heating load and an in-house emissions model based on the US EPA Wood Stove and Fireplace Emission Calculator (US EPA, 2009). Results from these models (BeOpt and calculator) formed the basis of the technical evaluation.

The emissions model used mass emission factors of PM_{2.5} and CO (Table S5) from the AP-42 Compilations (US EPA, 1996, 1998, 2008) as well as US Department of Interior (US DOI, 2014) emission estimates for local electricity generation, where applicable. All emissions were assumed to enter the ambient environment (e.g., no emissions entering the indoors). This step was necessary because there are no indoor emissions factors for this model. Based on the heating load of the Baseline Home, quantities of fuel consumed annually for each alternative were estimated (Eqs. 1–19 in Tables S6–S9) with assumed efficiencies (Table S10), electricity consumption (Table S11), fuel densities (Table S12), and heating values (Table S13). Annual emissions were calculated (Table S14) and

net annual reductions (Tables S15 and S16) and health benefits (Table S17) were compared to the Baseline Home. A summary of assumptions used in the technical assessment is presented in Table S18.

Multiple information sources were used to develop the costs and specifications of the options for each heating alternative and used as inputs for the emissions model (Table S19). Each option, within an alternative, represented a different combination of necessary components (e.g., one furnace type and one type of ducting for Natural Gas). The initial (i.e., materials and labor) and long-term (i.e., operation and maintenance) costs were determined from a total of ten information sources:

- 1) RSMeans Online 2015 Estimating Handbook for Farmington, NM (Gordian Group, 2015),
- 2) NREL BeOpt 2.3 Software Output for Farmington, NM (NREL, 2013a),
- 3) National Residential Efficiency Measures Database v 3.0.0 (NREL, 2013b),
- 4) Navajo Nation Utility Costs (Navajo Tribal Utility Authority, 2007),
- 5) US EPA Burn Wise Online Air Quality Tools (US EPA, 2013),
- 6) United States Department of Energy Buildings Energy Databook (US DOE, 2012),
- 7) Houck and Eagle (2006),
- 8) Franklin (2000),
- 9) Home Depot Online Catalog for Farmington, NM (Home Depot, 2015), and
- 10) Personal communication with Shiprock vendors (Table S20).

An example for Natural Gas follows: RSMeans Online (Gordian Group, 2015) was used to estimate labor and capital costs for one furnace retrofit with installation of associated ducting (option 1). This labor cost was then used to create new options using other furnace models from a local retailer's online catalog, leading to options 2 through 5. Each of these options had a different capital cost but the same labor cost. Next, the NREL Database was used to determine 8 more options. Houck and Eagle (2006) suggested two additional potential options, and one option was obtained via personal communication with a local contractor. These represent a total of 16 options ($n = 16$) for Natural Gas. Costs were annualized over the lifetime of each alternative (15–20 years).

Lastly, reductions in annual $PM_{2.5}$ emissions were translated into community health benefits (in US dollars) for the NN. The benefits-per-ton (BPT) values (Table S21) used were developed from existing residential wood combustion (RWC) emission inventories for the NN and EPA's Benefits Mapping and Analysis Software v 4.0.66 (BenMAP; US EPA, 2013). Emission (i.e., environmental) and health benefits were normalized to total net annualized costs (amortized initial cost + recurring heating and maintenance costs – wood fuel costs of Baseline Home) for each option of each alternative. This benefits analysis underestimates the benefits associated with RWC emissions reductions because: 1) it does not capture individual health impacts from indoor PM exposures, 2) it likely underestimates tribal RWC emissions inventories, and 3) it quantifies benefits from only a limited number of potential health effects (i.e., BenMAP considers 12 health effects).

3. Results and discussion

3.1. Community perception assessment of heating alternatives

The seven home heating alternatives identified by the stakeholders were ranked by Navajo community members (Section 2.4) using a scale of 0–5, with 5 being “very feasible”, applying the criteria listed in the footnote of Table S1A. Average total scores were calculated for each alternative resulting in the following order: Propane Gas (24.9), Electrical Heating (24.0), Passive Solar (23.6), Stove Replacement (22.8), Stove Improvement (22.5), Wood Pellet (21.4), and Natural Gas (18.8). Table S1B provides the results for each option and criteria listed

in Table S1A. Only results of the Perception Assessment that reached statistical significance (and shown in bold in Table S1B) are discussed here. For a given criterion, an alternative perceived as significantly different and lower than the other 6 alternatives was identified as least feasible. Conversely, an alternative perceived as significantly different and higher than the other 6 alternatives, was identified as most feasible.

Results showed that Natural Gas and Passive Solar were perceived to be least feasible in terms of availability, while Propane Gas and Electrical Heating were both perceived to be most feasible for that criterion. Natural Gas was also perceived to be least feasible in terms of infrastructure already in place (only 14% of households presently use natural gas delivered through pipelines) and least feasible in terms of cultural considerations (there are some cultural taboos against using natural gas). Propane Gas was perceived to be most feasible in terms of initial costs. On the other hand, Passive Solar was perceived to be most feasible in terms of long-term costs, while Wood Pellets was perceived to be least feasible for that criterion. No alternatives were perceived to be different in terms of maintenance needs.

Stove Improvement was perceived to be the least feasible (least beneficial) alternative in terms of environmental benefits compared to all other alternatives, while both Natural Gas and Stove Improvement were perceived to be least feasible in terms health benefits compared to the rest. Passive Solar was the only alternative perceived most feasible in terms of environmental and health benefits. Overall, Propane Gas received the highest total score, which can be interpreted as being perceived as the most feasible and beneficial alternative for use in NN homes for heating whereas Natural Gas was perceived to be the least feasible alternative. Stove replacement ranked fourth in this analysis, with no major perceived drawbacks or disadvantages.

The above analysis ascribed equal weight to all criteria; however, in practice, some criteria would be more important to this community than others. This assessment could be improved by assigning different weights to each criterion, according to the perception results obtained from this community.

3.2. Cultural assessment of heating alternatives

The Cultural Assessment was performed by the Diné Policy Institute (DPI) at Diné College. The goal of this assessment was for Navajo policy experts to identify potential barriers or incentives for the implementation of each of the 7 alternatives considered in this study. While the result of this process was not quantitative, it was critical for this Framework to generate recommendations.

Some relevant results and discussion are presented below. The descriptions closely reflect the language and views of the DPI and, therefore, may be less accessible to the regular reader; however, it is included for fidelity purposes. This also underscores the need for community participation and engagement to secure a successful intervention.

3.2.1. Natural gas and propane gas

Natural gas and propane are believed to be natural elements that originated from animals and plants that have decomposed over time and may not be seen as having negative effects on people. Appropriate protocol for accessing and utilizing them should be taken. Also, the blue flame created when combusted could be associated with a more dangerous form of fire, such as lighting. This flame is thought to burn hotter and could have negative effects on the body, such as gall bladder or lung related effects.

3.2.2. Electrical heating

Electricity is linked to energy of lightning, and thus should be treated with utmost precaution. Particular caution should be given to electrical heating sources that heat through direct contact with the human body. Electric blankets as an example, have been cause for some individuals to require ceremonies that can counter the effects. Electric heaters may

also have effects on people through drying of the air, including drying of the skin and nostrils.

3.2.3. Wood pellet

According to Diné teachings, wood is the preferred method of heating dwellings and cooking food. However, since wood pellet stoves require electricity, this reliance on electricity may be viewed as endangering one's well-being. Furthermore, some wood types are prohibited, such as Aspen and Cottonwood, since they belong to the snake family and produce a lot of smoke. If pellets were composed of these or other forms of prohibited wood, the effects could be negative for the person using the pellet stove.

3.2.4. Stove improvement and stove replacement

These stoves burn wood, coal, and/or wood and coal. From a cultural standpoint, naturally harvested cedar and oak are optimal for use in heating stoves, although pine and piñon are also acceptable. These woods produce red, yellow, or white fire flames, which are seen as the natural flames that represent Navajo sacred relative fires. The removal of coal from Mother Earth should be done with caution and proper protocols of respect and offering must be undertaken for accessing this element. Disregard for these protocols of respect and offering can lead to imbalance and negative effects to people who utilize coal.

3.2.5. Passive solar

The Navajo maintain a strong relationship with the Sun, the Father, as a holy being and sacred (*Diyyin*). From this connection, the Navajo were given the power of sunlight (*sháńdǫ́ín*) to use. However, this use needs to be done with control and care (e.g., prevent overexposure to avoid overheating). In general, sunrays are good, exhibiting positive energy. There is not a taboo against using the sunlight for energy, but some protocols are to be observed. For people to subsist with this energy is a way of life and to access the sun to heat one's home is not restricted. The idea of building according to the Sun is an ancient concept for Diné people. Building a home to orient to the Sun, such as with passive solar, can actually be seen as building according to nature and the path of the Sun, as long as the doorway faces the East.

3.3. Technical assessment of individual heating alternatives

The Technical Assessment consisted of three steps: 1) defining a Typical Navajo Home using BeOpt, 2) defining a Baseline Navajo Home by applying basic weatherization to the Typical Home and reducing its AAACH, and 3) applying each individual alternative to the Baseline Home and using an in-house emissions model to determine the environmental and health benefits of that alternative relative to the Baseline Home. Fig. 2 shows the three steps including key assumptions pertaining to home characteristics and household heating practices. Mean Initial Costs and Health Implications (benefits) are reported in the right-most column.

Table S22 summarizes the results of the Technical and Cultural Assessments for the heating alternatives on the basis of their availability (AV), infrastructure (IN), maintenance needs (MN), and cultural considerations (CC). Availability of Natural Gas was limited by access to gas pipelines, while Propane Gas, Electrical Heating, Wood Pellet, and Stove Replacement were limited by access to electricity. In this study, all the Stove Replacement options assessed had a built-in blower that requires electricity to improve combustion efficiency; however, they could be operated without the blower. Passive Solar is currently limited by access to affordable and effective technologies. Natural Gas, Propane Gas, and Electric Heating require the installation of ducting, a significant infrastructure change if not already in place in the home. Wood Pellet, Stove Improvement, and Stove Replacement are much simpler to retrofit and may utilize the existing flue. Infrastructure change for Passive Solar is extensive for an existing home, requiring installation of windows or construction of a Trombe wall. Maintenance needs vary

between \$100–167 yr⁻¹ for each alternative. Cultural Considerations include the blue flame color of gaseous fuels, the association of electricity with danger, the importance of wood type used in wood pellet production, and the over-exposure to sunrays.

Table S23 summarizes the results of the Technical Assessment on the basis of their Initial Costs (IC), Long-term Costs (LC), Environmental Implications (EI), and Health Implications (HI). Mean values for each alternative as well as the standard deviation (SD) and number of options explored (n) are presented. In terms of Initial Costs, Stove Improvement was the least expensive and Passive Solar the most expensive. For Long-term Costs, Stove Replacement was least expensive and Propane Gas was the most expensive. Natural Gas provided the most environmental and health benefits per dollar, while Propane Gas provided the least.

Fig. 3 integrates the results from the Perception (Section 2.4), Cultural (Section 2.5), and Technical (Section 2.6) Assessments to provide an overview of the results. Perception Assessment results were not normally distributed; thus, they are presented as boxplots. Discrepancies between the technical and perception assessments are indicated when the red diamond is outside interquartile range. Results from the combined assessments are as follows:

Natural Gas was perceived as less feasible in terms of availability, infrastructure, culture, and health implications. It provided the greatest benefits per dollar spent and had low long-term costs. Initial costs were comparable to other alternatives. Culturally, the blue flame often associated with gaseous fuels is believed to have negative effects on the body.

Propane Gas was perceived most feasible in terms of initial costs and availability. However, it provided the lowest benefits per dollar spent. Technically, Propane Gas had the highest initial and long-term costs. Culturally, there may be some concerns due to flame color.

Electrical Heating was perceived more feasible in terms of availability; however, it provided lower than average benefits per dollar spent. Initial costs were comparable to other alternatives, while long-term costs were higher than average. Culturally, heating with electricity is considered to have negative health effects on people.

Wood Pellet was perceived as least feasible in terms of long-term costs. It provided the second lowest benefits per dollar spent and the second highest long-term costs. Initial costs were comparable to other alternatives. Culturally, there may be concerns if pellets are made with unfavorable wood types or if wood type cannot be identified.

Stove Improvement was perceived as the least feasible in terms of both health and environmental implications. It provided lower than average benefits per dollar spent, but the initial costs were the lowest of all alternatives. Culturally, there were no apparent concerns, and wood fire is accepted as the traditional means of home heating.

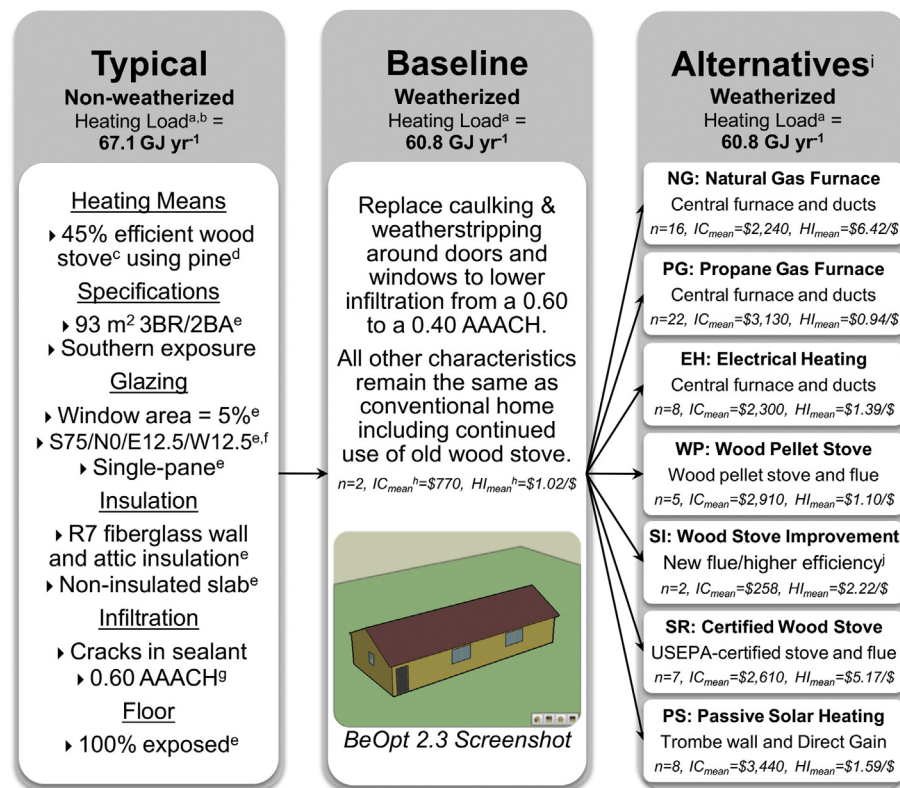
There were no clear negative or positive perceptions regarding Stove Replacement. Stove Replacement provided the second highest benefits per dollar spent. Initial costs were comparable to other alternatives. Stove Replacement had the lowest long-term costs. Culturally, wood fire is the traditional Navajo method of home heating and is widely accepted in the NN.

Passive Solar was perceived as the most feasible in terms of long-term costs, and was the most feasible in terms of both health and environmental implications; however, it was perceived to be least feasible in terms of availability. Passive Solar had lower than average long-term cost, but the initial costs were the highest of any alternative. The idea of building according to the Sun is an ancient concept for Diné people, and therefore culturally valued.

According to these results, SI, SR, and PS are viewed most positively by the Navajo culture, but SR shows the best combined results.

4. Conclusions

This study applies a newly established framework that takes into account community perceptions, relevant cultural considerations, and technical factors to evaluate replacement alternatives for home heating stoves in NN houses that potentially produce high levels of indoor air



- a. Heating load estimated by BeOpt 2.3 with a comfort temperature of 70°F.
- b. Value agrees with USEIA (2005a) estimate for the climate zone (CZ) in which the NN resides (CZ 2) (USEIA, 2005b).
- c. Low value (45.0%) from conventional wood stove range (41.7–63.1%) chosen (USEPA, 1996). Characterization of typical Navajo stoves is recommended; Hickmott et al. (1997) reported CO, NO_x, and SO₂ concentrations from a coal stove (*Warm Morning* model) commonly used in the NN, but no efficiency value. Hickmott reported peaks in gas-phase pollutants in the 15 minutes following addition of coal to a burning stove, and highly recommended further study and improvement of coal stoves for residential heating.
- d. Pine was most commonly used firewood in a survey of 45 Navajo homes near Ft. Defiance, AZ (Robin et al., 1996).
- e. Defined as Typical through personal communication with community leaders and brief visual inspection of Shiprock homes.
- f. Percentages of window areas on (S)outh, (N)orth, (E)ast, and (W)est sides of home; $\Sigma=100$
- g. AAACH defined as constant (A)nnual (A)verage (A)ir ex(C)hanges per (H)our. Value of 0.60 defined as “leaky” in BeOpt 2.0.
- h. IC = Initial Costs; HI = Health Implications
- i. Alternatives defined in terms of number of options analyzed (n) and their efficiencies $\{\epsilon=1-[(\text{Heat}-\text{Heat}_{out})/\text{Heat}]\}$ and heating capacities (BTU/time). Furnace and stove capacities are most often reported per hour, while passive solar model results are annual (Balcomb & McFarland, 1978; NREL, 2013b).
- j. Efficiency of “typical” Navajo wood stove (45.0%) improved to average of conventional wood stoves (53.6%) as defined by USEPA (1996).

Fig. 2. Summarized methods and results of technical assessment.

pollution. Two out of these three analyses depend completely on the Navajo Nation, highlighting the importance of engaging this community in the process. The current project applied a parallel convergent mixed-methods approach to balance the goal of reducing health and environmental impacts from solid fuel heating in the NN with the unique cultural and perceived preferences of Navajo families and with scientific analysis. To date, there exists no accepted framework to address environmental sustainability issues in communities with cultural and economic barriers to the adoption of cleaner technologies.

This assessment shows that weatherizing homes and replacing old stoves with cleaner more efficient models would be culturally acceptable, cost effective, and should reduce fuel use, improve indoor and outdoor air quality, and likely lead to improved health outcomes. To ensure that home heating stove changeout solutions are compatible with Navajo heating practices and traditions, it is critical to integrate the sustained involvement of Navajo leaders and community members in the process.

Due to varying levels of fuel availability and affordability, and to ensure cultural suitability, a successful intervention will require a mixture of approaches and should include freedom of choice for fuels and stove types. Attention must be paid to common heating practices, such as the

use of both wood and coal in the same stove. In that regard, EPA is pilot testing new dual-fuel (wood and coal) stoves to see if a cleaner dual-fuel stove can be developed that meets wood stove emission standards. Educational initiatives should accompany any changeout program to explain the benefits and health implications of each heating alternative in a culturally relevant manner and to ensure proper operation of new stoves (Table S24).

A settlement agreement between EPA and several electric utilities is providing funds for a stove change out and weatherization program in the NN for homes near the Four Corners Power Plant. To validate and communicate the anticipated improvements in air quality, indoor and outdoor air measurements should be undertaken before and after alternatives are instituted, and participants should be surveyed to assess satisfaction with their new stove. Stove replacement should lead to reductions in adverse health and air quality impacts from residential heating on the Navajo Nation, as recommended by Bunnell et al. (2010).

This combined assessment helped uncover areas where community perception, culture, and the technical analysis align as well as where there are discrepancies that will necessitate increased dialogue regarding healthier heating methods. It is important that cultural experts in the community (e.g., here the Diné Policy Institute) write a thorough cultural assessment to achieve an effective

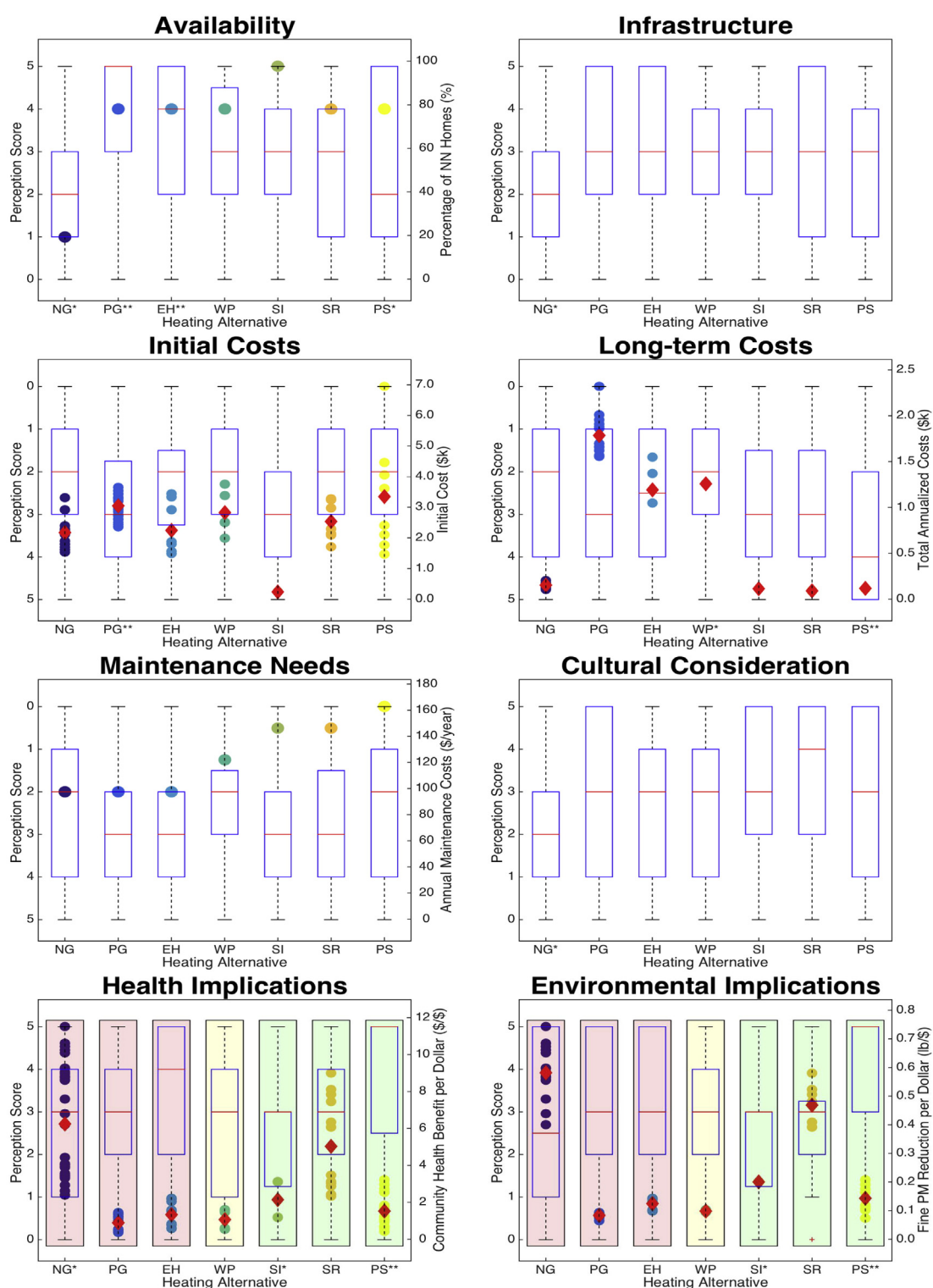


Fig. 3. Integrated results of perception, cultural, and technical assessments. The perception assessment is indicated as boxplots on the y-axis and a higher score is perceived as more feasible based on the criteria evaluated. The red line represents the median perception score for that alternative, the bottom and top lines in the box represent the first and third quartiles representing the interquartile range (IQR), the whiskers represent 91% and 10%. For the criteria quantified by cost (IC, LC, and MN), a higher perception score would be perceived as “more feasible” or less expensive; therefore, the left y-axis (and quartiles) are flipped for these alternatives. Alternatives perceived as least feasible are denoted with * next to their initials and those that are most feasible are denoted with ** on the x-axis. Results of the Cultural assessment were superimposed on the HI and EI sub-panels, where red, yellow, and green shading represent overall negative, neutral, or positive results from the cultural assessment, respectively. Results of the technical assessment are shown as dots. Dot colors represent a heating alternative, while each dot represents a different option (Section 3.3). The red diamond is the mean technical assessment for all options for that alternative, also shown in Table S23. The right y-axis shows the results of the technical assessment, with the lower and upper limits of the y-axis defined as zero and approximately the maximum value for that criterion, respectively. The technical assessment did not include infrastructure or cultural considerations because they were not defined in a manner that could be quantified.

integration of culture and science. The framework used for this study may be applicable for other Native American Nations, such as the nearby Hopi Nation, where climate conditions and coal use are similar to those of the NN.

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Appendix A. Supplementary data

A total of 25 Tables and 1 Fig. are included as Supplementary information, which provide detailed information used by the three-tiered Navajo Framework. Supplementary data associated with this article can be found in the online version, at <http://dx.doi.org/10.1016/j.scitotenv.2016.11.053>.

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