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Bamboo Construction in Bhutan: a feasibility and market study

Oliver Frith, Nripal Adhikary and Sonam Peldon,
with Prabhat Kr. Mukhia and Gyeltshen Dukpa

Foreword

Bamboo and Rattan are of growing importance to the Ministry of Agriculture & Forests (MoAF) in Bhutan, and even to international organizations. Bamboo and rattan can contribute significantly to conserving the natural environment and enhancing rural livelihoods. Bamboos are known to be a poor men's timber; easy to grow, manage and harvest in a short period of time. In comparison, timber takes a long gestation period to attain its maturity.

Bhutan's membership of INBAR has provided the skills/capacity on the bamboo house construction and treatment techniques. A lot of benefits in terms of information sharing and networking, capacity building through training opportunities have been offered to the Ministry of Agriculture & Forests.

The Common Fund for Commodities (CFC) project & INBAR's support for bamboo for sustainable construction and rural value chain development in Bhutan has given new ideas on promoting bamboo house construction with modern engineering technology. Through the assistance of the CFC project and INBAR, we are grateful that the Department of Forests & Park Services could come up with construction of prototype bamboo houses. The focus is to educate the students and younger generation on the conservation of forests, use of bamboo for environmentally friendly construction and to help them understand conservation closely through observation. As a highly renewable resource with excellent construction properties, bamboo is well placed to substitute for timber in construction.

The bamboo commodity development approach will help in providing the existing Community Forest Management Groups with new livelihood and income-earning opportunities. Through the above measures, our initiatives will provide a foundation for long-term financial sustainability, as well as pave the way for up-scaling and replication of bamboo sector development across the country.

Chencho Norbu
Director General
Department of Forests and Park Services

Hans Friederich
Director General
International Network for Bamboo and Rattan

Bamboo is one of the oldest and most versatile building materials in the world, with enormous potential to help meet the growing construction needs of Bhutan. However, while the country has a proud and diverse architectural heritage that has included the use of bamboo for many generations, to date, applications of the material are mostly restricted to non-structural and lower-grade buildings.

Therefore, in this groundbreaking study, INBAR and Bhutan's Social Forestry and Extension Division (SFED) provide a framework for how bamboo can fulfill its true potential as a mainstream building material and source of sustainable local livelihoods.

The study not only assesses the potential feasibility and markets for expanding use of round culm bamboo in construction in Bhutan, but also helps to unlock some of the traditional challenges to building with the material, such as its poor natural durability, lack of standardized joints, and exclusion from building codes. The result is a comprehensive study that sets out practical recommendations for developing a formal national bamboo construction sector that can help to conserve Bhutan's forests, support local employment and provide quality housing for all.

At INBAR, we now look forward to continuing our partnership with Bhutan and to helping make the recommendations in this study become a reality. I urge you to join us in achieving this goal.

Acronyms

BTN	Bhutanese ngultrum
CEFS	Conservation, Environment and Forestry Studies
CFC	Common Fund for Commodities
CFMG	Community Forest Management Group
CUF	Capacity Utilization Factor
DOFPS	Department of Forest Park Services
DZFS	Dzongkhag Forestry Services
GIS	Geographical Information System
INBAR	International Network for Bamboo and Rattan
IRR	Internal Rate of Return
NPV	Net Present Value
NRDCL	Natural Resource Development Corporation Limited
NRED	Nature Recreation and Eco-tourism Division
NWFP	Non Wood Forest Product
WCD	Wildlife Conservation Division
RNR – RDC	Renewable Natural Resources – Research – Research Development Center
SFED	Social Forestry Extension Division
UWICE	Ugyen Wangchuck Institute for Conservation and Environment

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Executive Summary

Bamboo, a lightweight, locally available, highly renewable and naturally strong material, with excellent earthquake resistant properties has the potential to play a key role in meeting future building needs in Bhutan. With a growing population and increasing demand for construction material, Bhutan urgently needs to identify new environmentally friendly construction materials. The Kingdom is constitutionally committed to maintaining forest cover above 60% for all time, with bamboo being one of the best locally available timber substitutes. Situated in the Himalayas, Bhutan is also highly prone to earthquakes, making bamboo construction materials an ideal option for future buildings.

However, traditionally, bamboo use in Bhutanese construction has been limited, with the nation facing a number of challenges to mainstream use of the material. These include both social stigmas attached to the material, which is widely regarded as a material for the poor, as well as technical challenges related to bamboos' poor natural durability, labour intensive nature, and lack of available mechanical property data and design values. To compound these challenges, Bhutan's bamboo resources, while very diverse, are also highly limited and often under pressure from local domestic consumption.

Acknowledging these challenges, the Royal Government of Bhutan joined INBAR in 2010 with the goal of developing its bamboo sector, especially for construction. To support this goal, from May 2012 to April 2014, INBAR and the Social Forestry Extension Division (SFED) jointly implemented a Common Fund for Commodities (CFC)-funded project entitled "Bamboo for Sustainable Construction and Rural Value Chain Development in Bhutan: a pilot project". The CFC provided US$120,000, covering 60% of the total project cost, with INBAR and the Royal Government of Bhutan providing co-finance of 40%. In addition to supporting initial pilot work in *Zhemgang, Samdrupjongkhar, Tsirang and Samtse* Dzongkhags under the project, this study was also commissioned to assess the feasibility and identify markets to mainstream the use of unprocessed round culm bamboo as a construction material.

The study makes use of a number of methods for collecting and analyzing data, including literature reviews, household surveys, rapid resource assessments, key informant interviews and financial analysis. Through the study, a number of important findings were made. Firstly, the study highlighted the crucial role that bamboo already plays in many rural economies, both formal and informal. For example, *in Zhemgang*, community groups earn annual incomes of roughly US$3,000 from selling bamboo shoots, culms and finished products. In all 4 Dzongkhags covered by the CFC project, bamboo was also a vital on-farm input used for the construction of fencing and sheds. Despite its obvious importance, the study also found that bamboo resources were often under stress from over-consumption, with a statistically significant trend of reducing availability of resources being reported in project areas with traditionally larger bamboo coverage.

Although lack of bamboo resources is a potential roadblock to bamboo development, financial analysis for setting up bamboo plantations in Bhutan suggests that they can by financially viable and provide raw bamboo at competitive prices with neighbouring states in India.

Furthermore, while we observed that there were still large social acceptance challenges to building with bamboo, recent demonstration projects have highlighted how bamboo can be incorporated into traditional vernacular designs. Furthermore a number of objections to building with bamboo were also found to be technical in nature – namely its lack of durability, the perceived labour intensiveness of working with the material, as well as a lack of knowledge of basic mechanical properties. Subsequently, INBAR has already developed new construction systems and introduced new treatment technology, which allow for easy pre-fabrication of durable construction products. For example, this study has shown that these systems can be used to build roof trusses that could be up to roughly half the cost of equivalent trusses built from 1st class conifers.

The study also found that the importance of bamboo to the rural economy is now well reflected in national legislation, with community-based management of bamboo able to follow similar establishment processes as for any other type of community forestry management group. However, while good legislation frameworks are in place, the study also found that implementation of the legislation was often hindered by weak coordination and a lack of monitoring and evaluation mechanisms.

Based on our findings, we conclude that a bamboo construction sector in Bhutan has the potential to be viable from economic, social and technical perspectives. In order to realize this potential, the study makes a set of 5 key recommendations to guide future development:

1) Target construction markets for bamboo building components rather than houses;
2) Continue to collect more data on the mechanical properties of local bamboo species and improve design protocols;
3) Develop an official guideline for building with bamboo in Bhutan;
4) Develop an accurate inventory of all bamboo species and set up a National Bamboo Resource Management and Development Plan;
5) Improve bamboo sector planning and coordination to fully implement existing policy frameworks.

Introduction

This study forms part of a Common Fund for Commodity-funded Project, "Bamboo for Sustainable Construction and Rural Value Chain Development in Bhutan: a pilot project", which was implemented in *Zhemgang, Samdrupjongkhar, Tsirang and Samtse* Dzongkhags (Figure 1), and which was part of a partnership between INBAR and the Social Forestry and Extension Division (SFED), Department of Forests and Parks Services, Royal Government of Bhutan to trial and set up demonstration value chains for bamboo construction. The study attempts to assess the feasibility and identify markets for developing the bamboo construction sector beyond demonstration and pilot activities and is aimed at policy makers, entrepreneurs, community forest management groups (CFMGs) civil society, and international development organizations working in Bhutan, who have an interest in establishing a formal bamboo construction sector.

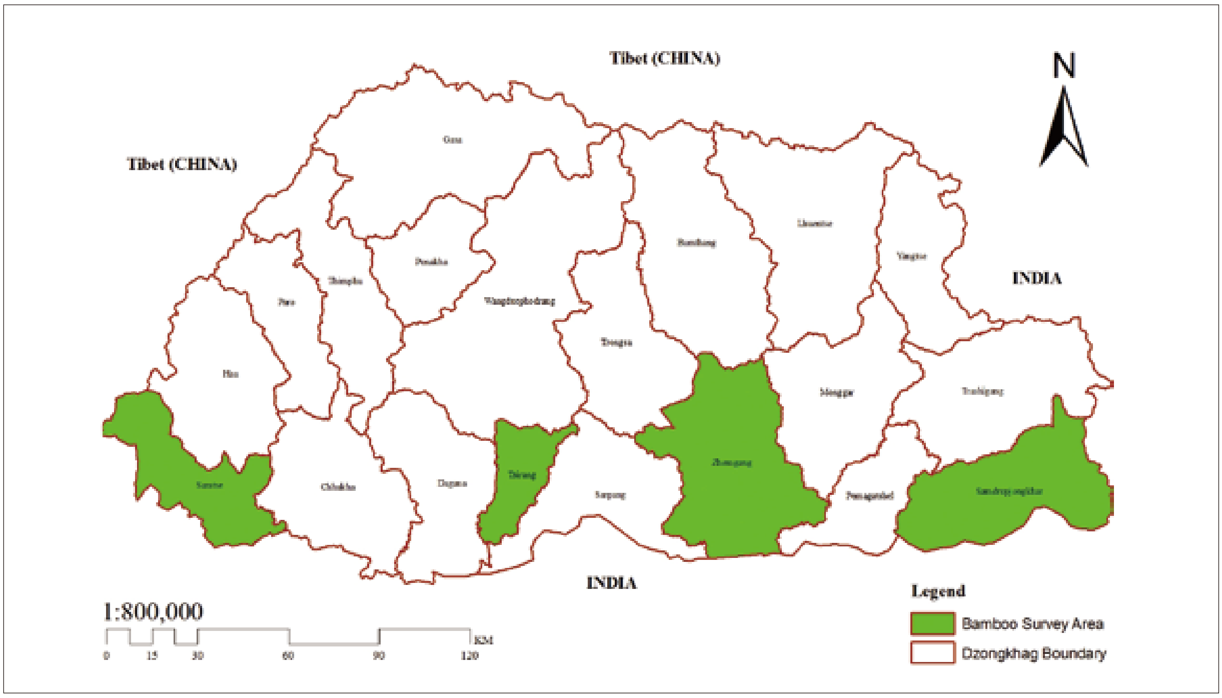

Figure 1: Location Map of Dzongkhags covered under this study

The study assesses potential structural market applications for unprocessed, round culm bamboo which is locally available and relatively inexpensive, and thus well-suited for applications in rural settlements. Although engineered bamboo panel and lumber products that have similar properties to equivalent timber products are produced in other Asian countries, such as India and China (Xiao, et al., 2007), and could play a role in meeting Bhutan's future construction needs, these products do not form part of the CFC-funded project and are beyond the scope of the present study.

The study has the following main objectives:

1. To evaluate the feasibility of establishing a formal bamboo construction sector from social, technical, environmental, and economic perspectives;
2. To assess the current status of bamboo resources and utilization trends, and the policy environment in Bhutan;
3. To provide recommendations on how to form a commercial bamboo construction sector, including suggestions for policy interventions and potential value chain and business models to achieve commercialization.

The study is split into six sections. In the first section, we review the current status of construction in Bhutan, with a focus on timber buildings. We then assess the technical and social feasibility of using locally-available bamboo species to act as substitutes for mainstream construction materials. To aid our assessment of bamboos' feasibility for use in construction, we review examples of bamboo demonstration structures that have been built in *Zhemgang*, *Samtse* and *Tsirang* Dzongkhags.

In section two of the study, we then address the lack of mechanical property data for local species, the predominant barrier to using bamboo in construction in Bhutan. New research on developing a simple testing set-up, which can rapidly generate data in rural settings and is appropriate to the current socio-economic condition of Bhutan, are presented here.

In section three, we review some construction products (improved bamboo greenhouses and trusses - prototyped in Nepal and Bhutan) that could be made from bamboo and that could have applications in the domestic market, and compare them with mainstream products.

In section four, we review the current status of the bamboo sector in Bhutan. Here we focus on assessing the environmental sustainability of building with bamboo at varying degrees of scale. To do this, we analyze resource inventory and baseline rural household data collected in our four target Dzongkhag*s*.

In section five, we assess the economics of producing bamboo for the construction industry. To do this, we analyze the costs for bamboo propagation, treatment and final supply of treated culms in Bhutan. These costs are then equated into expected costs of using bamboo in construction. To illustrate these costs, we use structural truss products as an example, comparing bamboo with conventional timber equivalents.

Finally, in section six, we summarize our findings and provide a list of key recommendations for the Royal Government of Bhutan that we feel could help to support the development of a formal bamboo sector.

Section 1: Current Status of Construction in Bhutan

One of the main motivations behind the CFC-funded project on bamboo construction value chains, was the 6.1-magnitude, 2009 Mongar Earthquake in Bhutan that claimed the lives of 10 people and damaged hundreds of buildings (Figure 2). This event raised serious concerns about the safety of construction in Bhutan, especially that of vernacular masonry and timber structures, which, in some cases, were badly damaged during the earthquake (Langenbach, 2010). In addition to these concerns, with growing population and construction needs, there is a danger that timber resources in the country will be insufficient to meet future demand. For example, until a recent government ban on loan facilities for developers, there were severe annual timber shortages in the country (Chhetri, A. and Pradhan, N., 2013 – personal communication).

Pressure on supply is also compounded by the Government's constitutional commitments to maintain forest cover of 60% for all time, while also providing housing for all. Finally, given that Bhutan also faces a major Balance of Payments challenge, there is an urgent need for the country to control imports and promote domestic production and consumption (Kinga, 2012). Therefore, in this section of the study, we review traditional construction techniques in Bhutan and assess the feasibility of using bamboo as a substitute construction material.

Figure 2: Damaged traditional timber & masonry structures after 2009 *Mongar* earthquake

In theory, due to its lightweight and high natural strength[1], local bamboo resources can act as anti-seismic (Janssen, 2000; Gutierrez, 2004; Jayanetti, 2003) substitute construction materials to timber, while, at the same time, helping to maintain vernacular architecture traditions. This is particularly relevant to Bhutan's context, where cultural heritage is covered under the 4th article of the Constitution. In Bhutan, there are a number of vernacular models in place for using *shingzo* (woodwork) and *dozo* (masonry) in construction, with these two techniques belonging to the thirteen traditional arts and crafts of Bhutan. In addition, rammed earth construction has a rich heritage, particularly in the west of the country. In comparison, the use of bamboo in construction is rare and usually restricted to the country's southern belt. In most cases, bamboo is only used for non-primary load bearing applications, such as wall infills (*Ekra*). To assess how bamboo could be integrated into traditional design as a substitute for timber, we review common vernacular building typologies below and then present examples of bamboo demonstration housing built by the Department of Forest Park Services (DoFPS), with technical support from INBAR, over the past three years.

[1] some of its mechanical properties surpass those of oak wood

Traditional Bhutanese Architecture

Traditional Bhutanese houses, typically made from timber, stone, clay and adobe brick, have unique design features compared to other Himalayan countries. Homes were often built up to 3-storeys high, with the ground floor providing room for livestock. Furthermore, between the third floor and the roof, an open space is typically kept for open-air storage.

Figure 3: Traditional Bhutanese House

Bhutan's common vernacular building techniques can be classified into various categories. Firstly, non-reinforced masonry load bearing walls with timber floors and roofs are a common building technique. These structures were among the more badly damaged during the 2009 earthquake. In addition to this system, many houses are also built using a timber frame, which is infilled with woven wood or bamboo slats, and then plastered on both sides (Figure 4). This system is also often used in upper story walls on top of an underlying masonry wall. Timber-framed structures are also commonly built with rammed earth walls, which are typically built to a minimum thickness of 60cm (Sethna, 2008). In these structures, solid rammed earth walls are built on all four sides of all but the top floor of the structure, where a timber frame with a bamboo infill (erka wall) is used and then plastered on both sides (Figure 5). Bundles of bamboo or wood planks are also often inserted into the corners and middles of the rammed earth on the lower floors, helping to stabilize the walls and improve seismic performance.

While bamboo has not been used in load bearing frames in Bhutan, there are plenty of experiences from other countries where this approach has been successfully applied (e.g. NBC 2005; Government of Bihar, 2010; Kaminski, 2013). Therefore, bamboo could potentially replace timber in housing frames, while maintaining many of the original features and characteristics of the original vernacular design.

Figure 4: Traditional Bhutanese Timber Structure

Figure 5: Erka bamboo house common to South Asia

Regardless of type, almost all traditional buildings employ timber roof systems, with the most common type being the gable roof. This roof is made from a heavy principle beam (*Gungchhen*), which is supported by a series of vertical posts, known as *Shari, Sha-thung*, *Lhiuchung*, and *Ga* (Department of Urban Development and Housing, 1995). The roof is generally supported in the middle and rear of the house on raised rammed earth, known as *Chholo.* Rafters (*Tsim*) are placed on the principal beams and fastened to closely-laid roofing battens (*Dhangchung*). The final roof is finished with timber shingles that are held down by stones over the lath. In recent times, corrugated sheets and roofing tiles have been used to replace shingles. Building on this gable roof technique, *jamthog* and *lung-go* roofs are made by building a second raised gable above the original roof structure. The second roof layer respectively extends to either the full length of the lower gable (*jamthog*) or part of the length (*lung-go*). Importantly, the heaviness of these traditional roofing systems represents a potential weakness in design, which conforms poorly to commonly accepted earthquake-resistant design practice (Sethna, 2008). In the future, turning timber roofing and flooring, used in both traditional rammed earth and masonry homes, into functioning diaphragms could improve protection against future earthquakes (Langenbach, 2010). Given the above, with its round, hollow, and lightweight nature, the utilization of bamboo in roofing could represent a major opportunity for improving the seismic performance of structures, while maintaining the original aesthetic of the vernacular design (see sections 2 & 3).

To demonstrate how bamboo can be integrated into traditional architecture, DoFPS have built three hybrid bamboo-timber/concrete frame structures in *Zhemgang*, *Samtse and Tsirang* Dzongkhags. Below we provide a brief description of these demonstration structures and how they integrate bamboo into traditional construction practices.

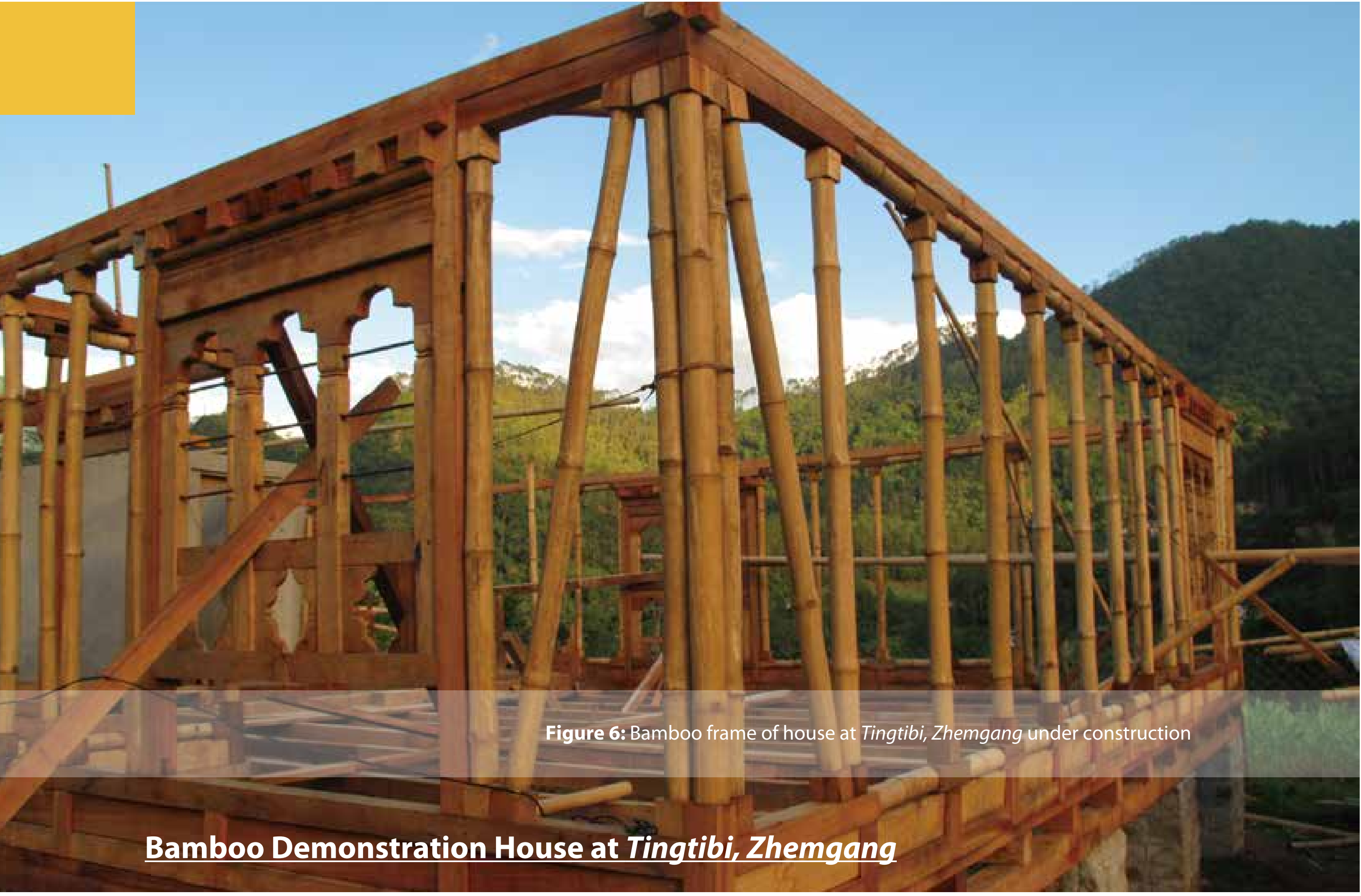

Figure 6: Bamboo frame of house at *Tingtibi, Zhemgang* under construction

Bamboo Demonstration House at *Tingtibi, Zhemgang*

In December 2011, the first bamboo-framed, traditional-style house in the country was constructed and handed over to the Dzongkhag administration of *Zhemgang*. The 100m^2 community house, jointly designed by INBAR and Dzongkhag engineers, was constructed by SFED in *Tingtibi, Zhemgang* District.

The house adapts traditional Bhutanese timber frame techniques for bamboo (Figure 6), aiming to demonstrate how to use bamboo as an effective alternative to timber, whilst ensuring cultural acceptability of the house.

The new structure uses local bamboo species (*Bambusa tulda* and *Bambusa nutans*) as the framework of the house and for many of the walls, with timber still used for joints, whilst the use of traditional adobe walling and a thatched roof ensures that all materials, except the cement used in the foundations, were sourced locally. The house uses approximately 25.5m^3 less wood than an equivalent timber-framed home, and is nearly half the price, at a cost of US$140/m^2 (authors own observation). All the bamboo used in the construction was also treated with borax and boric acid using the boucherie treatment technique (see section 5), thereby ensuring a minimum service lifespan of 20-25 years.

Figure 7: Completed bamboo demonstration house at *Tingtibi, Zhemgang*

Bamboo Demonstration Structures in *Samtse* Dzongkhag

Following construction of the bamboo house at *Tingtibi* and feedback from the local community (see next sub-section), SFED also commissioned and built another three bamboo structures in *Samtse* Dzongkhag. These structures use more manmade construction materials than the house at *Tingtibi*, with a primary load-bearing concrete frame being supported by a secondary bamboo frame made from *Dendrocalamus hamiltonii* var. hamiltonii and *Bambusa nutans* subsp. cupulata. However, the structures use the same bamboo treatment and jointing systems for bamboo member connections (see section 2) as the earlier bamboo house at Tingtibi, as well as adopting techniques commonly used in India. One of the structures located in *Pakpay* is now being used as a community centre, while two structures built in Samtse Town are being used as a conservation hall and transit camp.

Figure 8: Bamboo/concrete frame hybrid under construction at *Pakpay, Samtse*

Figure 9: Completed bamboo community center at *Pakpay, Samtse*

Figure 10: Completed bamboo conservation hall at *Samtse Town, Samtse*

Bamboo Demonstration Structures in *Tsirang* Dzongkhag

Finally, in 2014, the *Tsirang* Divisional Forest Office, with technical support from SFED, also successfully built a modern bamboo house, using three locally available species - *Dendrocalamus sikkimensis, Bambusa tulda* and *Bambusa nutans*. Based on this experience, CFMG members of *Pemathang* under *Goserling Gewog, Tsirang* Dzongkhag also built their own office - cum-meeting hall with bamboo. This bamboo structure, which was built with financial incentives of Nu.107000.00 from SFED, is the first of its kind to be constructed by a CFMG in Bhutan. The experiences in *Tsirang* further highlight the potential of applying modern bamboo construction techniques to rural areas of Bhutan and beyond.

Figure 11: Completed bamboo house at Tsirang Divisional Forest Office

Figure 12: Completed CFMG office-cum-meeting hall at *Pemathang, Tsirang*

Social Perceptions of Bamboo Housing

While the above demonstration projects show that local species of bamboo do have potential to substitute for timber in traditional buildings, construction of these buildings has also shown that a number of technical and social barriers still exist to introducing bamboo into traditional building systems. Firstly, local attitudes to bamboo, and traditional natural building materials in general, were found to be highly negative. Communities didn't believe bamboo homes would have a long life and felt that these houses would be highly vulnerable to storms and fire. The vast majority of community members now aspire to live in concrete homes, which they associate with higher social status.

It was also found that many people lacked the knowledge or skill to build with bamboo. This was highlighted by the large building delays SFED and INBAR experienced during the construction of demonstration structures, with the lack of skilled artisans being a major contributory factor (Norbu, Y. 2013 – personal communication). With no guidelines or codes in place for bamboo construction, the general perception of local people was that building with bamboo was complicated (Wangchuk *et al*., 2011). Therefore, our experiences show that development of a bamboo construction sector is contingent on overcoming both technical and social barriers.

In the next two sections of the study, we provide details on how technical barriers could be overcome by placing an emphasis on product development for specific components of housing, where the use of bamboo may be more easily accepted. In the final section of the study, we also provide recommendations on how to address both the social and technical challenges of promoting this new alternative building material.

Section 2: Bridging Technical Barriers to Construction with Bamboo in Bhutan

Building with bamboo in its natural round-pole form involves overcoming several technical challenges. For example, there is widespread acknowledgement that one of the main barriers to using whole round bamboo is its non-uniformity (Xiao *et al*., 2007). Slight variations along the length of the culm (taper) and larger variations between individual culms, coupled with its hollow circular nature, mean that building with bamboo requires considerable skill.

At present, to the best knowledge of the authors, Bhutan does not have any guidelines or codes of practice for using bamboo in construction. Neither the Bhutan Building Code (BTS-009-2003), nor Bhutan Building Rules 2002 document, cover the use of bamboo construction materials. However, the Department of Human Settlement, Ministry of Works and Human Settlement, did include a chapter on bamboo in their recent publication "Guidelines for Planning and Development of Human Settlements in Urban and Rural Areas of Bhutan to minimise environmental impacts" ([a] Ministry of Works and Human Settlements 2013). Although this document is very useful for raising awareness about bamboo's potential, it includes no technical information on building with bamboo. Furthermore, the recent release of Rural Construction Rules 2013 by the same Department makes no reference to bamboo ([b] Ministry of Works and Human Settlements 2013).

Given these challenges, it is not surprising that most current construction with bamboo has been limited to either informal structures built off - code, or to demonstration structures, with a high degree of on-site management and oversight. Therefore, we introduce the technical and design work that has been funded by the CFC project in Bhutan, which may help to overcome some of these existing challenges.

Simplifying Design and Construction with Bamboo

As with timber-framed construction, the structurally most vulnerable parts of bamboo buildings are the connection joints. Connections are also often the most technically challenging parts of any building. Though some aspects of bamboo connection design are similar to timber, many factors prevent direct transfer of techniques. For example, with its round, non-rectangular, nature, the contact area between two bamboo members is theoretically a point, not a surface. Furthermore, due to its hollow nature, the strength of a bamboo connection relies on only a small contact area between a fastener and a member. Finally, bamboo is tapered and generally not perfectly round, meaning that producing carpentry joints is highly time-consuming and hard to replicate on a large scale.

In order to address these issues, connection systems which can be easily fabricated and will help local artisans and community members to build more conveniently with bamboo were developed in the project. The various jointing systems are described below.

Bamboo-Wood Joint

This joint was successfully trailed during construction of the first demonstration bamboo house in *Tingtibi, Zhemgang*. The joint connects two bamboo members in a load-bearing frame via a wooden connection (Figure 13). Wood square wood members are rounded using a chisel and inserted in the ends of bamboo. Similarly, connections between two pieces of wood use mortise and tenon joints reinforced with bamboo dowels. This joint allows artisans and carpenters to transfer traditional skills from woodwork to bamboo. The success of this method was highlighted by the fact that carpenters trained at *Tingtibi* were able to replicate the joint and teach production of it to others without any supervision or guidance on subsequent demonstration structures built in Samtse.

Advantages of the Bamboo-Wood Joint:
- Uses local materials
- Can be standardized
- Economical in places where wood is abundant.
- Quick to install

Disadvantages of the Bamboo-Wood Joint:
- Requires specialized carpentry skills
- Not economical in places where wood is scare

Figure 13: Bamboo-wood joint connecting two bamboo members

Bamboo-Rattan Joint

This joint appropriates traditional weaving techniques from Bhutan. The two connected bamboo members are joined using a fish-mouth joint. The T-sections are then connected with woven rattan.

Advantages of the Bamboo-Rattan Joint:
- Uses local materials
- Has good aesthetic values

Disadvantages of the Bamboo-Rattan Joint:
- The joint is not suitable for heavy roofs or multi-storey buildings
- Rattans are not available every where.
- Rattan can take as much as 20 years to mature
- Requires specialized skills.

Figure 14: Bamboo-rattan joint

Jute-Epoxy Joint

In this connection, bamboo is first connected using a fish mouth joint. The bamboo is then reinforced with jute fiber, which is coated with epoxy.

Advantages of Jute-Epoxy Joint:
- Can be used for building light weight structures
- Uses fibers and epoxy which are easily available
- Very strong

Disadvantages of Jute-Epoxy Joint:
- Labor Intensive
- Uses epoxy, which has higher embodied energy

Figure 15: Jute-epoxy joint

Metal Joints

This joint has two components. The first one uses round steel, which has 6 flanges of 3cm. The bamboo has metal plate connections, which connect to the first components with nuts and bolt. The flanges and nuts-bolt allow 90-degree movement, which is a useful feature for making space trusses.

Advantages of the Metal Joint:

- Standardized joint
- Can make 3 Dimensional spaces trusses - required for large span structures
- Quick and easy to fabricate
- Unskilled labourers can install the joint
- Strong
- Economical when savings on time of labour are considered

Disadvantages of the Metal Joint:

- Uses steel which has high embodied energy

Figure 16: Metal joint

Metal Brackets

This joint has two components. The first one uses round steel, which has 6 flanges of 3cm. The bamboo has metal plate connections, which connect to the first components with nuts and bolt. The flanges and nuts-bolt allow 90-degree movement, which is a useful feature for making space trusses.

Advantages:

- Quick and easy to fabricate
- Unskilled labourers can install the joint
- Strong
- Economical if savings on time of labor are considered

Disadvantages:

- Uses steel which has high embodied energy

Figure 17: 3-d metal joint

Non-Destructive Mechanical Strength Grading of Bamboo

In addition to design work, INBAR has also developed a portable testing kit set up to non-destructively grade the strength of individual pieces of bamboo in the project. The aim of the kit is to minimize designer uncertainty about the strength properties of bamboo, which can vary widely between individual culms. In theory, this approach will help to develop a standard design practice for bamboo culms, which will increase ease of use and safety in the built environment. Furthermore, with more available data, designers, who currently have to build in a highly conservative manner with the material, will be able to use bamboo in a more efficient manner.

Figure 18: INBAR-developed portable strength grading test kit

The special testing sets are designed to be simple to operate, affordable, robust, point-of-use devices that are suitable for both rural and urban areas of Bhutan (Figure 18). These devices test the ability of an individual culm to withstand specific types of loads, thereby satisfying fundamental design criteria, such as strength or stiffness. Full details of the portable testing kits and their set up are given in INBAR's Working Paper "Draft Bamboo Building Guidelines for Bhutan" (Adhikary, in press). Here, we focus on reporting the results of the current testing, as well as the theory behind the tests.

The initial focus of INBAR's testing work has been on two commonly used structural members - beams and columns. The project team has developed special testing kits to determine the load bearing capacity of a bamboo culm in these applications.

For beams, INBAR has developed a simple, portable 3-point bend test kit. The test is carried out on a fixed span. The set-up uses support blocks and loading blocks made from angle iron that provides a natural V to keep the round bamboo culm stable. The set up is calibrated using a steel tube as a test piece. This kit plots a load W – deflection Δ graph for the steel tube. The slope of W/Δ is proportional to the Flexural Rigidity E*I of the tube. The value of the proportionality constant ₭ for the set up is determined using the known values of E & I for the steel tube and the value of W/Δ determined from the calibration test. This set-up is then used to test any number of bamboo culms, keeping the position of the supports and loading block fixed, thereby ensuring that ₭ does not change. W/Δ for each culm is determined and from it the value of E*I for the culm is calculated (Chaturvedi, 2013). Based on this we can also calculate the safe bending moment, which is proportional to the maximum measured value of W (the value of safe bending moment = W*L/4).

Given the above two values, a designer can then readily select a specific grade of culms that meets both required strength and rigidity criteria for use in a beam application. Although the range of these values in the available grades may be limited, with additional care in selection of the bamboo culm parameters of length and density, a designer can use well-known and established principles of design to make the structure acceptable. The deficiency of a limited range can also be partially overcome using a larger number (perhaps 2 or 3) of culms as a single beam (Chaturvedi, 2013).

In addition to beams, the team has also developed a test set-up for measuring loads when a bamboo culm of up to 3m in length is used as a column. Here the derived EI value for bamboo can be used to design long columns based on Eulers formula for calculating maximum/critical force, i.e. vertical load on a column (Chaturvedi 2011):

$$F=\pi^2 EI/(KL)^2$$

Where
F = Maximum or critical force (vertical load on column)
L = unsupported length of column

Based on the above work, INBAR has now already taken preliminary test readings for beam applications of several bamboo construction species found in Bhutan. The range of values recorded for one of these species, *Bambusa balcooa*, during preliminary testing along with the calculated range in load carry capacities are shown in table 1 below. All bamboos have been tested for 4m-long spans. The table also includes comparable data for steel.

Test specimen	W/DEFL. (kg/mm)	EI (*10^6) (Kg.mm2)	CR. LOAD (4m long)	Diameter (mm)	WT/M (Kg/m)	EI/Wt/m (Max)	EI/Wt/m (min)
STEEL	9.170	1970	2428	42.50			
Sample 1	5.210	1119	1379				
Sample 2	2.985	641	790	56.70	1.134	565.494	498.672
Sample 3	3.748	805	992	55.43	1.285	626.604	487.630
Sample 4	4.729	1016	1252	54.43	1.346	754.781	560.759
Sample 5	3.023	649	800	56.67	1.000	649.434	649.434
Sample 6	4.156	893	1100	60.57	1.330	671.306	504.742
Sample 7	3.279	704	868	53.87	0.980	718.807	733.476
Sample 8	3.409	732	903	55.10	1.206	607.263	503.535
Sample 9	6.609	1420	1750	67.00	1.590	892.967	561.615

Table 1: Summary of preliminary bending test results for *B. balcooa* compared to steel

While the above values should not be extrapolated beyond the context of this particular test, the results show that for the tested specimens a 100mm diameter bamboo culm would perform as well as 50mm diameter steel for load carrying beam applications. With further testing, this data could form a basis for Bhutan to further refine its list of bamboo priority species for construction.

Importantly, the authors would like to reiterate that this data is only preliminary and under no circumstances should be used as design values for untested batches of bamboo. Furthermore, there is likely to be great variation within species, especially from samples taken from different geographical locations. While a great deal of further testing and development work is therefore still required for structural uses of bamboo in Bhutan, this section provides an overview for how technical challenges to larger-scale bamboo construction could potentially be overcome.

Section 3: Potential Bamboo Construction Products for the Bhutanese Market

In this section of the study, we introduce a few potential market opportunities for promoting the use of bamboo as a structural material. Our selection of products and markets takes into consideration existing building practices and traditions. Given that there are certain potential stigmas and misconceptions attached to building with bamboo (see section 2), we have attempted to identify applications where bamboo may be more easily accepted, i.e. as a component in a building or a public/community structure, rather than building entire structures from bamboo. Importantly, the suggestions should not be taken as a definitive list of feasible options. In addition to the products introduced below, demonstration buildings, such as the ones presented in section 1, can also continue to play an important role in awareness raising and building local capacities.

Roof Trusses

The use of bamboos for roof trusses appears to be one of the most feasible options for promoting the mainstream use of bamboo in the Bhutanese construction sector. Both traditional and contemporary structures in Bhutan have pitched roofs, with trusses traditionally being made from timber. However, today, many Bhutanese are switching to metal trusses.

Our study shows that bamboo could be an alternative, environmentally sustainable, roof truss building material (see table 2). Bamboo can take the compressive load of metal sheets or wooden shingles, typically used in roof sheeting, as well as the lateral load of wind or earthquakes. Moreover, since bamboo trusses are used on the interior of a structure and have almost no or very limited contact with the weather, treated materials (see section 5) can achieve the same levels of durability as other conventional materials. Furthermore, our work shows that trusses built with locally available bamboo species can be built at up to 10 meters of free span, which meets the requirements of many residential and public buildings.

Figure 19: Bamboo Roof Truss

BILL OF QUANTITIES - STRAIGHT SECTION:		
6 meter span truss		
Brackets per truss	10	
Barell nuts	120	
Bamboo Length	326	meters
Labor Days	30	man days
Paint	3	liters
Number of Trusses	5	
8 meter span truss		
Brackets per truss	15	
Barell nuts	180	
Bamboo Length	489	meters
Labor Days	45	man days
Paint	6	liters
Number of Trusses	5	
10 meter span truss		
Brackets per truss	20	
Barell nuts	240	
Bamboo Length	587	meters
Labor Days	60	man days
Paint	6	liters
Number of Trusses	5	

Table 2: Bill of Quantities for bamboo trusses of 6, 8 and 10m spans

Description	Comparison points		
	Bamboo Truss	Steel Truss	Wood Truss
Durability	20-25 years	50 years	30 years
Income opportunity to the communities	Yes	No	Yes
Environment friendly	Yes	No	No
Easy to transfer technology to the local communities	Yes	No	Yes
Possible to make large scale structures	Yes	Yes	Yes

Table 3: Comparison of bamboo, steel and wood trusses

In section 5, we will compare the projected costs of building structural members with bamboo and equivalent wood-based alternatives.

Greenhouses

Recently, the Horticulture Division, Department of Agriculture, Ministry of Agriculture and Forests started a new subsidy programme to support the establishment of greenhouses in Bhutan. This scheme forms part of efforts to commercialize vegetable production and reduce dependency on agricultural imports. The subsidy works as a cost-sharing scheme, with the Division providing 40% of the greenhouse cost and the farmer the remaining 60%. At present, all the greenhouses are being imported from India. The greenhouses are GI pre-fab units that come in 50m^2 and 100m^2 sizes. The costs of the greenhouses are BTN 57,000 and BTN 95,000 respectively (Dorji, 2013 – personal communication).

The development of greenhouses represents another potential niche market for bamboo as a construction material. For example, in *Wengkhar, Mongar* District, the Research and Development Centre has already developed a prototype design for a bamboo greenhouse (figure 20). Furthermore, some communities currently make rudimentary greenhouses with bamboo by themselves. However, these community designs tend to perform poorly in bad rains and have short durability.

Figure 20: Research and Development Centre Bamboo Greenhouse Prototype

If improved greenhouse designs can be developed, this would help to deliver the Government subsidy scheme at potentially far lower costs, while also completely eliminating reliance on imports, a stated aim of the initiative.

Therefore, as part of this CFC-funded project, INBAR has developed further prototype designs for bamboo greenhouses. These kinds of greenhouses may have an edge over conventional materials, because they are light weight, can be produced locally by farmers, and have good durability, provided that treated bamboo is used. As described in section 2, we have now also developed a unique method of connection using metal that means the structure can be pre-fabricated, with its light weight making it easy to install.

Comparison points	Greenhouse type	
	Bamboo	GI
Durability	10 years	20 years
Community income generation	Yes	No
Environment friendly	Yes	No
Technology easily transferable to communities	Yes	No
Possible to make large scale structures	Yes	Yes

Table 4: Comparison of greenhouses made from bamboo and steel

Tourism infrastructure

The tourism industry represents another sector where bamboo has high potential to be incorporated into infrastructure development. Bhutan's tourism industry is "founded on the principle of sustainability, meaning that tourism must be environmentally and ecologically friendly, socially and culturally acceptable and economically viable" (Tourism Council of Bhutan, 2014). Within this context, bamboo could play a key role in the development of tourism infrastructure that is not only culturally appropriate and ecologically sound, but also economically feasible. In a number of other countries in Asia, bamboo has already been used to good effect to deliver tourism infrastructure for both high-end luxury resorts and retreats and lower end accommodation. Therefore, in Bhutan, it may also be feasible to promote bamboo as a construction material within the tourism sector, with several agencies providing a good entry point for such work.

For example, the recently established Nature Recreation and Eco-tourism Division (NRED), Department of Forest and Park Services, Ministry of Agriculture and Forests is now tasked with supporting Dzongkhag and National Parks to build tourism infrastructure, such as gazebos, eating places, pavilions, trails, signposts, and guesthouses. NRED also work closely with the Tourism Council. Their work currently covers nature recreation, ecotourism, and environmental education. Although NRED have primarily been using timber and stone masonry, there is potential in bamboo, especially in the south of the country (Gyeltshen, N. 2013 – personal communication). This would fit well with Government directives to use local materials as much as possible.

Section 4: Current Status of the Bhutanese Bamboo Sector

Having observed that there are good potential solutions for overcoming technical and social constraints to building with bamboo, in this section we assess the current status of bamboo resources and utilization in Bhutan. The overall aim of this section is to assess the environmental feasibility of expanding construction with bamboo based on the present status of the sector. Before introducing our findings, it should be noted that data on bamboo resources is restricted to the four Dzongkhags covered under the CFC - funded project - *Zhemgang, Samdrup Jongkhar, Tsirang* and *Samtse*. Therefore, the study does not cover all of the bamboo growing regions in the country. Despite this, based on our discussion and interviews with SFED staff, it is fairly safe to assume that our findings for the project-covered sites are representative of the current national situation.

Current Bamboo Resource Availability and Utilization

At present, there is no national inventory of bamboo resources for Bhutan. However, in 1994, Stapleton recorded 15 genera and 31 species of bamboo in Bhutan, including three with large diameter culms suitable for use in construction (Stapleton, 1994). In the CFC project, the project team has predominantly worked with *Bambusa tulda*, *Bambusa nutans*, and *Bambusa balcooa*, which are all species that can be used for structural applications. Therefore, Bhutan does have the required plant material for bamboo construction. However, our field experience has shown that the availability of this material is limited. To assess current resource availability, SFED has conducted a rapid resource assessment for the four CFC-covered target Dzongkhags, *Zhemgang, SamdrupJongkhar, Tsirang* and *Samtse* (Mukhia, 2013). For this study, SFED surveyed bamboo coverage for both Government Reserved Forest Land (GRFL) and Private Registered Land (PRL) in Community Forest Land (CFL) in each Dzongkhag. The main results of this inventory assessment are given below.

The resource assessment found 19 species of bamboo in the surveyed areas, among which, 12 are used in structural or non-structural construction applications. Table 5 below gives a list of the species surveyed and their local uses.

Scientific Name	Local Names	Local Uses
Bambusa alamii	Dingso (Sha)/Mugi bans (Lho)	Light construction
Bambusa arundinacea	Katha/valka / kanta bans (Lho)	Heavy construction
Bambusa balcooa	Dhanu bans (Lho)	Heavy construction
Bambusa clavata	Chiley / Chile bans (Lho) &Pagshing (Dzo)	Light construction
Bambusa nutans subsp. Cupulata	Mal bans/Mola bans/Moli bans/Magla bans /Makla bans /Mala bans (Lho)/ Tsai (Khe)	Construction
Bambusa tulda.	Bangay bans/Shingaray bans/ Singari/Shingaray/Shingari/ Shigari bans (Lho)	Heavy construction
Bambusa vulgaris	Teli bans (Lho)	Construction
Cephalostachyum capitatum	Phusrey bans/Phursenigalo/ dulloo bans (Lho)/Jhi (Dzo)/pishima (Khe)	Mostly for bamboo mats; can be used in construction
Chimonobambusa callosa	Karey bans / Karay bans (Lho)	Used to make rough type of bamboo mat
Dendrocalamus giganteus	Balu / Bhalu bans (Lho)	Good construction
Dendrocalamus hamiltonii	Shushing (Khe) and Guliyo tama bans (Lho)	Construction, average quality
Dendrocalamus hamiltonii	Songopa / So, Lishing or leeshing (Sha),Choya or tama bans (Lho) or Tsu (Khe)	Construction
Dendrocalamu hookeri	Bom bans (Lho)	Construction
Dendrocalamus sikkimensis	Demchar/Demcharbu/Demtshar/Dem chherring (Sha)/Bhalu bans (Lho)	Construction, average quality
Drepanostachyum spp.	Kalang (Sha)/Nigalo (Lho)	Construction of huts
Neomicrocalamus andropogonifolius	Yula (Khe)	Handicrafts
Pseudostachyum polymorphum	Filling or Philling bans (Lho) / Dai (Khe)	Construction of huts
Yet to identify	Dara bans (Lho)	Beams in hut construction
Yet to identify	Serlingay bans (Lho)	Construction of huts

Table 5: Different species of bamboo found during bamboo survey (Mukhia 2013)

NOTE: Abbreviation of the languages (Kha means language)
Sha = Sharchopkha, Lho = Lhotsamkha, Dzo = Dzongkha, Khe = Khengkha

Figure 21: Uses of bamboo in Bhutan for homestead fencing and basketry

The survey also found that bamboos played an important role in local rural livelihoods in all Dzongkhags, where bamboos are commonly used for the production of household utensils and handicrafts, the erection of homestead fences, as raw materials for *erka* and small-scale construction, as fodder for cattle, and as a dietary supplement in the form of edible shoots (figure 21). Furthermore, in *Zhemgang*, community groups also made annual incomes of roughly US$3,000 per year from selling shoots, culms and finished products.

However, despite the diversity of bamboo genera and species and the importance of bamboo to local rural livelihoods, the survey also found that available resources are generally limited and, in some cases, poorly managed. This is particularly true of *Zhemgang*, where the volume of bamboo culms per hectare was the lowest of all four surveyed Dzongkhags (see table 6). These findings are also in line with previous work who found that in the last 8 years, commercial bamboo species resources, such as *Neomicrocalamus andropogonifolius* have drastically declined (Dorji, 2013). During this time the number of clumps and culms available for harvest of this species have fallen by almost 90% and 97%. Local communities in *Zhemgang* have now started using other big bamboo species to produce handicraft items (Mukhia, 2013).

Dzongkhag	Samtse	Samdrupjong	Tsirang	Zhemgang
Area of farmed bamboo (ha)	972.40	92	236.70	135.93
Area of wild bamboo (ha)	9.724	9.20	11.84	20.39
Total bamboo area (ha)	982.12	101.20	248.54	156.32
Total clump (nos) / ha	64	72	137	93
Total culm (nos) / ha	1,630	1,939	4,959	1,637
Total vol. by clump (m^3) / ha	102.23	276.81	162.81	189.67
Total vol. by culm (m^3) / ha	96.31	255.70	152.57	9.67

Table 6: Average bamboo coverage& availability in CFC project Dzongkhags (Mukhia, 2013)

In addition to the rapid resource survey, SFED also took a baseline survey of 200 randomly sampled households across the four project Dzongkhags. The main summary of the baseline survey is shown below in table 7.

Dzongkhag	*Samtse*	*Samdrupjongkhar*	*Tsirang*	*Zhemgang*
Mean total household income (BTN)	62350	54346	181430	117610
Mean raw bamboo income (BTN)	327.45	232.20	243.30	255
Mean processed bamboo product income (BTN)	126.42	80.00	24.49	14873
Mean household bamboo consumption (culms)	16.02	25.60	42.47	38.58
Mean bamboo shoot consumption (kg)	0.66	0.00	0.10	26.30
Mean household land holding (ha)	1.88	1.20	1.85	2.17
Mean household forest holding (ha)	0.02	0.01	1.01	0.02
Mean household bamboo forest holding (ha)	1.38	0.23	0.06	0.004

Table 7: Summary statistics from 2012 baseline survey of CFC project target households

The rapid resource assessment and the household baseline survey both show that local bamboo resources are highly limited and are used largely for household consumption and local markets. These results are also in line with findings from previous SNV Bhutan and SFED-led bamboo and cane feasibility studies in *Samtse* and *Sarpang* Dzongkhags ([b] long et al, 2010). Furthermore, the results suggest that resources are in danger of being over-exploited in areas where bamboo has become an important commercial resource. For example, in *Zhemgang*, our results suggest that if consumption for our randomly sampled households is extrapolated to the 2,534 rural households living in the Dzongkhags this equates to consumption of roughly 98,000 culms per year. However, based on the average number of culms available per hectare in our resource inventory and assuming a harvest rotation of 3 years, only 77,000 culms can be sustainably harvested from the available surveyed resource base.

Similarly, our survey data for *Samdrup jongkhar* suggests the Dzongkhags could have a supply gap of up to 83,000 culms per year. While our data also suggests that *Samtse* and *Tsirang* both seem to have excess annual consumption capacity of roughly 314,00 and 216,000 culms respectively, we do not have species-specific inventories and therefore cannot determine the precise availability of construction grade bamboo material. It should be noted that for all Dzongkhags, we were not able to assess resources on privately own lands, which could also be an important source of bamboo.

Interestingly, using post-hoc test of a one-way ANOVA analysis ($F(2,196) = 4.696$, $p = .010$) of our baseline household data, we also found a statistically significant result that suggests that in households where bamboo resource availability is generally higher, farmers tended to report that the resource base is declining, whereas in areas with a lower resource base availability farmers tended to report that the resource base is growing. Means of bamboo forest area of groups reporting increased and decreased cover trends are 0.138 ± 0.043 Acres ($p = .008$) and 2.785 ± 1.18 Acres ($p = .008$) respectively. This result is consistent with a general pattern of resource exploitation followed by restorative management practices being implemented after resources drop to a certain threshold.

Coupled with the issue of limited resource availability, local communities currently lack fundamental skills and knowledge to sustainably manage and utilize their existing bamboo stocks. At present, communities rely almost entirely on propagation with whole bamboo culm offsets (Personal Observations 2012 & 2013). While this method is appropriate for use in farm homesteads, it is an inefficient method for plantation development. Furthermore, due to lack of appropriate knowledge on culm selection, survival rates in Bhutan are often poor. While RNR RDC in Gelephu, South Central Bhutan, has done some trial work using bamboo branch cuttings, very little capacity still exists at the community and technical extension service level.

The lack of locally available bamboo resources is also highlighted by the prices of bamboo in Bhutan, which can be as high as BTN130 per culm. In comparison, in neighbouring Indian states a culm typically costs just BTN50-60. At present, Bhutan imports over 136,000 culms per year from India ([b]Long et al., 2010), which is predominantly used in urban areas as scaffold (figure 22).

Figure 22: Bamboo scaffold in Thimphu, Bhutan

Current Status of Planting Material

Generation of suitable bamboo planting material is a major challenge facing the development of Bhutan's sector. To date, the total bamboo plantation area in Bhutan is more than 178ha, of which 7ha have been planted under the CFC project. As the CFC project has highlighted, due to their rareness and short viability, bamboo seeds are usually not available for plantation development. During this CFC project, SFED imported seeds of *Bambusa tulda* from Dehradun, India, which were grown in nurseries in *Samtse* and *Sarpang*. However, only 20% of the *B. tulda* seeds germinated. In addition to these issues, the longer maturation time of bamboo seedlings and their wide genetic diversity makes it harder to set up plantations for desired genotypes with superior construction characteristics, such as higher density, large diameter, straightness, limited taper, and strength. Table 8 shows some pros and cons of various planting materials for bamboo:

Type	Pros	Cons
Seeds	• New Generation (long life) • Diversity of Genotypes • Low cost • Small plant/ Easy transport • Logistic advantage • Opportunity for selection and macroproliferation	• Limited availability • Limited viability • Long time needed before plants are ready for planting (9-12 months)
Offsets (Division)	• Quality guaranteed • Type guaranteed • Success rate high with most species • Opportunity for selection and macroproliferation	• Bulky plants • Very labor intensive • Long time needed to propagate lots of planting material • High logistic costs • Large propagation area needed • Shorter life cycle than for seeds • limited clonal diversity
Cuttings (culm & branch)	• High capacity (for some species; success rate varies with species) • Type guaranteed • Fast growth	• Shorter life cycle than for seeds • Long time needed to propagate large amount of material • bulky plants - high logistic costs • large propagation area needed
Tissue Culture	• Mass production • True-to-type plants • Vigorous plants with multiple new shoots • Very fast growth & high biomass production • Small & vigorous • Logistical advantages	• Limited clonal diversity • Shorter life cycle than seed produced plants • High investment needed for propagation • Large orders usually required

Table 8: Pros and Cons of Various Types of Bamboo Planting Materials (Brias, 2013)

The lessons from the CFC project show that considerable planning will be needed to develop planting material in Bhutan. SFED is already working with community groups in bamboo growing areas to set up nurseries (Figure 23). Based on local conditions and capacity, SFED should now trail different propagation techniques to ascertain which techniques deliver the best results in terms of quality of material and economic viability. Several INBAR publications are available, which can act as a reference in this area (e.g. Banik, 1995 and Poppins, 2004)

Figure 23: Bamboo nursery in Samtse, Bhutan

Sector Policy & Coordination Environment

While there is currently a limited availability of construction-grade bamboo material in Bhutan, we did find that the country already has a good enabling policy framework that, with further capacity building and coordination of local resource managers, could support future sector development. Firstly, the latest Forest and Nature Conservation Rules (2014), which form the legal basis for the use and management of forest resources in Bhutan, include provisions for Non - Wood Forest Products (NWFPs). In line with these rules, the Interim Framework for Management and Marketing of Non Wood Forest Products (2009) & the National Forest Policy (2011) allow for commercial use of NWFPs provided there is an approved management plan. Therefore, in principle, community-based management of bamboo or any other NWFP can follow similar establishment processes as for any other type of community forestry management group. Initial research from Bhutan SNV suggests that community management of NWFPs can lead to improved outcomes for both bamboo resources and beneficiary communities (Meijboom et al., 2008).

In addition, the National Strategy for the Development of Non-Wood Forest Products in Bhutan, covering the years 2008-18 (Social Forestry Division, 2008), also provides guidance on priority species for bamboo and links enhancement of the bamboo sector to broader NWFP development and marketing goals. SFED heads a working group under the interim framework for this strategy that brings together key bamboo sector institutional stakeholders, such as the Natural Resource Development Corporation Limited (NDRCL), a 100% Government-owned corporation which is solely responsible for timber supply and investment in the country, the Wildlife Conservation Division (WCD), and the Renewable Natural Resources – Research Development Center (RNR - RDC).

Within this existing policy framework, there have already been some commercial attempts to develop bamboo. For example, NDRCL attempted to sell bamboo from Southern Bhutan in Thimphu for scaffold and matting. The attempt failed at that time primarily because the available selection of bamboos was poor (poles were not straight enough for scaffolding use). Furthermore, as previously mentioned, the local bamboo prices are often higher than the typical cost in neighbouring India (Chhetri and Pradhan, 2013 – personal communication).

In recent times, NRDCL have planted 7ha (2012) and 6ha (2013) of bamboo plantations in *Samtse*. However, the first attempts at bamboo plantations were done on a “trial and error basis” (Chhetri, A. and Pradhan, N., 2013 - personal communication). Priority species for commercial exploitation were not identified. NRDCL is still interested to work with bamboo and has classed bamboo as one of three major alternatives to replace domestic timber, the other two being imported timber teak and fibre cement board (Chhetri, A. & Pradhan, N., 2013 – personal communication).

While Bhutan does have a good policy framework in place, these initial sector development experiences show that existing policy frameworks need to be better implemented and further strengthened. Notably, from interviews with SFED staff, we found that the interim-working group for bamboo under the NWFP strategy has not met for well over a year. Furthermore, at present, SFED is yet to develop a monitoring and evaluation system (M&E) to assess and guide policy actions, while Dzongkhags M&E results are not recorded and collated nationally. The results from inventories, surveys and key-informant interviews also clearly show that Bhutan (e.g. Mukhia, 2013) will need to make significant investments in bamboo resource development and management in order to develop a commercial construction sector. Therefore, in the next section of this study, we analyze the economics of bamboo resource development and supply to assess the feasibility of scaling up the sector.

Section 5: The Economics of Bamboo Resource Development and Supply

Financial Analysis of Plantation Establishment

Given the current status of bamboo resources in Bhutan, in order to establish a formal bamboo construction sector in Bhutan, it is clear that significant investments in bamboo propagation must be made to expand the resource base. To assess the potential costs, we conducted a financial analysis on establishing plantations for commercial bamboo construction species. It should be noted that as commercial propagation of bamboo in Bhutan is in its infancy, a number of assumptions have had to be made in the following analysis. Importantly, in most countries with commercial propagation, fertilizers and irrigation are widely employed. However, this is not currently the case in Bhutan (Ghimeray, K.N., 2013 – personal communication). To estimate potential yields we used experiences from other neighbouring countries in South Asia (Banik 2000; Shanmughavel et al., 1997). Therefore, the actual yields produced and costs of production will need to be thoroughly assessed by SFED and partners over the next 5-10 years.

In our analysis, we relied primarily on information provided by Mr. KN Ghimeray from the Nursery and Plantation Section of the Social Forestry and Extension Division, as well as rates given in SFED's "Norms and Standards for Nursery and Plantation (revised version 2008)" (*Social Forestry Division*, 2008). For all our calculations, we assumed a discount rate of 14%, which is the approximate average value for commercial bank interest rate loans in Bhutan (Ghimeray, K.N,, 2013 – personal communication). Given its current prominence as a propagation method in Bhutan, we used rhizomes as the propagule unit of analysis in our calculations. For nurseries, we took the current selling price for a bamboo rhizome used by SFED, BTN 50, as the input cost for planting materials used in plantations (KN Ghimeray, 2013 – personal communication).

For our financial analysis of bamboo plantations, we primarily assessed the importance of size of plantation in determining costs. To do this, we compared a 1ha start-up plantation with a 5ha start-up one, based on actual costs incurred during the CFC project in *Samtse*. For all plantations we assumed a plant spacing of 5m by 5m, which is advised for a combination of hilly terrain, common to most parts of Bhutan, and large sympodial bamboo construction species. Flowering cycles for bamboo can range from 3-120 years, with observed cycles for species in South Asia often ranging 30-50 years (Banik, 2000). As we cannot be sure of the original age of rhizomes used in plantations, in our study we set the expected plantation lifetime at 20 years. Below in table 9, we give a full list of the assumptions we used for our calculations for 1ha and 5ha plantations.

ASSUMPTIONS – plantations

	Rate	Units	Source
Discount Rate	14%		SFED
Project Life	20	*Years*	Banik
Propagation method	Rhizome	*NA*	
Plantation spacing	5*5	*Meters*	
Rhizomes per hectare	400	*Seedlings/ha*	SFED
Cost of land	0	*BTN/ha*	SFED
Cost of labour	165	*BTN/day*	SFED
Fixed costs in yr. 1 for 1ha plantation	34980	*BTN*	SFED
Fixed costs in yr. 1 for 5ha plantation	64970	*BTN*	
Tax and Royalties	Not incl.		
Salvage value at end of the project	0	*BTN*	
Site survey requirements			
1. 1ha plantation	2	*Workdays*	SFED
2. 5ha plantation	6	*Workdays*	SFED
Site Clearance		*Workdays*	
1. 1 ha plantation	20	*Workdays*	SFED
2. 5 ha plantation	150	*Workdays*	SFED
Alignment and stacking		*Workdays*	
1. 1 ha plantation	8	*Workdays*	SFED
2. 5ha plantation	35	*Workdays*	SFED
Planting of Rhizomes		*Workdays*	
1. 1 ha plantation	112	*Workdays*	SFED
2. 5 ha plantation	570	*Workdays*	SFED
Deployment of fencing		*Workdays*	
1. 1ha plantation	81	*Workdays*	SFED
2. 5ha plantation	313	*Workdays*	SFED
Erection of signboard	4	*Workdays*	SFED
Weeding in year 1-5 after planting	15	*Workdays/ha/yr*	SFED

Fence Maintenance			
1. 2nd year after planting	10%	*Posts & nails %*	SFED
2. 3rd year after planting	20%	*Posts & nails %*	SFED
3. 4th & 5th year after planting	30%	*Posts & nails %*	SFED
Fence Maintenance – workdays			
1. 2nd year after planting	2	*Workdays/ha/yr*	SFED
2. 3rd year after planting	4	*Workdays/ha/yr*	SFED
3. 4th & 5th year after planting	6	*Workdays/ha/yr*	SFED
Rhizome casualty replacement			
1. 2nd year after planting	30%	*Seed casualty %*	SFED
2. 3rd year after planting	20%	*Seed casualty %*	SFED
3. 4th year after planting	10%	*Seed casualty %*	SFED
Workdays replacing Rhizome casualties			
1. 2nd year after planting	16	*Workdays/ha/yr*	SFED
2. 3rd year after planting	12	*Workdays/ha/yr*	SFED
3. 4th year after planting	6	*Workdays/ha/yr*	SFED
General Maintenance years 5-20			
1. Removal of dead/unwanted plants	20	*Workdays/ha/yr*	
Harvesting workdays			
1. Harvest starts 4th yr after planting	33	*Workdays/ha/yr*	
2. 5th year after planting	44	*Workdays/ha/yr*	
3. 6th year after planting	55	*Workdays/ha/yr*	
4. 7th year after planting	66	*Workdays/ha/yr*	
5. 8th year after planting	78	*Workdays/ha/yr*	
6. 9-20th year after planting	88	*Workdays/ha/yr*	
Harvest volume			
1. Harvest starts 4th yr after planting	400	*Culm/ha*	INBAR
2. 5th year after planting	530	*Culm/ha*	INBAR
3. 6th year after planting	667	*Culm/ha*	INBAR
4. 7th year after planting	800	*Culm/ha*	INBAR
5. 8th year after planting	940	*Culm/ha*	INBAR
6. 9-20th year after planting	1067	*Culm/ha*	INBAR

Table 9: Assumptions used for financial calculations of bamboo plantations in Bhutan

For the financial assessment, we use two main tools to assess the viability of commercial projects. Firstly, given the known existing costs for establishing and maintaining bamboo plantations in Bhutan and assuming harvested culms will be sold at cost parity with culms from neighbouring India (BTN50/culm), we calculate the Net Present Value (NPV) of establishing and managing a 1ha and 5ha plantation. NPV is the difference between the discounted cash inflow and discounted cash out flow of a project, i.e. it converts all costs and revenue into present day monetary values. If NPV is greater than zero, i.e. discounted inflows (revenues) are higher than discounted outflows (costs), a project is generally deemed to be financially viable.

In addition to calculating NPV for bamboo plantations, we also calculated the Internal Rate of Return (IRR) on investment. The IRR for an investment or project is the discount rate at which the present value of all future cash flow is equal to the initial investment, i.e. the rate at which an investment breaks even. IRR calculations are commonly used to evaluate the desirability of investments or projects. The higher a project's IRR, the more desirable it is to undertake the project. Here we argue that plantations are viable if they deliver a rate of return higher than the typical bank interest loan rate of 14%.

Table 10 shows a summary of the main results for the plantation projects.

	1 ha plantation	5ha plantation
Internal rate of return	14%	19%
Discounted cash inflow	217839	989394
Discounted cash outflow	170902	656968
Net Present Value	46937	332426
Benefit/Cost ratio	1.27	1.51

Table 10: Financial analysis summary of 1ha and 5ha bamboo plantations

Interpretation of calculations

Based on market prices of BTN50 per culm, which represents cost-parity with bamboo culms currently sourced from India, a 5ha plantation would generate an estimated NPV of BTN 332,426. This indicates that the plantation would be financially viable. Furthermore, a 5ha plantation selling culms at BTN50 would generate an IRR of 19%. This is above the rate of a typical bank loan and represents a viable return on investment. For a 1ha plantation, due to the smaller economies of scale and using a sale price of BTN 50 per culm, NPVs and IRRs are lower than for 5ha plantations. The respective NPVs and IRRs are BTN 46,937 and 14%. This suggests that the viability of 1ha plantation would be marginal at cost parity culm sale price with neighbouring India.

Figure 24: Modified boucherie treatment plant

Figure 25: A nozzle connecting bamboo

Bamboo Resource Supply and Treatment

While bamboo propagation in Bhutan appears to be a viable business, if bamboo is to be utilized in high-quality construction, it must be chemically treated. In comparison with wood, bamboo has relatively poor natural durability, making it particularly prone to fungal, termite, and pest attack. Typically, untreated bamboo has a maximum lifespan of five years (Liese and Kumar, 2003). While there are also many traditional, non-chemical treatment practices for bamboo, such as water immersion and smoke curing, the efficacy of these treatments is variable and usually offers only protection for a maximum of up to 10 years. For commercial applications, INBAR recommends that chemical treatment regimes be used, which, provided appropriate design are employed, can ensure a minimum lifespan of 20-25 years. Among chemical treatment methods, the authors have personally found that pressure treatment methods, where pressure is used to displace sap in bamboo culms with preservatives, produce the most reliable results (Adhikary, 2007). Therefore, although non-pressurized treatment methods, such as dip diffusion, are widely used in some regions of the world (e.g. Colombia), in this study we focus our analysis on pressure treatment methods only. This section of the study provides financial analysis on the annualized cost of producing treated bamboo culms using the modified boucherie method. The pressure chamber method is also described here and costs of setting up a plant in Nepal converted into BTN are provided[2].

Before we introduce the financial analysis, we will briefly describe the two treatment methods and their relative strengths and weaknesses. In modified boucherie method, also known as the sap displacement technique, a pressurised preservative solution is applied on the basal end of a bamboo culm, which pushes the sap contained in the vascular bundle out and then replaces it with the preservative. This technique is only possible on a freshly cut bamboo, while the vascular bundle is still open and must therefore be applied within 24 hours of harvesting bamboo (Liese and Kumar, 2003). A typical boucherie treatment kit consists of a big cylinder - in this CFC project, we used a 50 litre capacity cylinders fitted with the following components:

- *Pressure gauge*: The pressure inside the cylinder is always kept at 30-35 psi, which is enough to send the solution inside the bamboo.
- *Solution inlet*: The mixed solution is poured through this inlet.
- *Solution regulator*: This regulates how much solution is let out of the cylinder.
- *Hand pump*: A simple manual pump to put pressure into the cylinder. An electric compressor can be used if labour is expensive, and electricity is available.
- *Pressure regulator*: To regulate how much pressure is to be let inside the cylinder.
- *Solution outlet*: In our project we split this into 7 outlets, to let the solution out.

[2] At present, no such facilities in Bhutan have been set up and so local costs are not readily available against which to make a calculation

Figure 26: A closer look at a nozzle connecting bamboo

Figure 27: Men and women using the treatment plant

Figure 28: Bamboo pressure chamber treatment unit

The main advantages of this treatment technique are that is very easy to operate and is portable. Therefore, treatment can take place directly at the site of felling and communities themselves can administer treatments. This method also requires no alteration to the length of the culm, apart from cutting to required section lengths. Therefore, it also produces nice finishes, which are not only ideal for use in construction, but also in round-culm furniture making. INBAR has demonstrated this treatment method in many rural areas, where more than 50% of the operators are often women (Figure 27).

BOUCHERIE TREATMENT STEPS

1. The cylinder is ¾ filled with preservative using boric acid, borax and water at a ratio of 1:1:10.
2. The cylinder is pressurized (up to 30-35 psi) using a simple manual pump or a motorised pump wherever electricity is available.
3. The valve in the nozzle is pressed open for a split second to let the air out.
4. The nozzle is connected to the bamboo, which is made airtight using a customised rubber hose (see Figure 26).
5. Sap starts dripping from the branch after approximately 5 minutes. It takes about half an hour for the preservative to come out from the opposite end.
6. Treatment should last for at least an hour so that the preservative can reach all parts of the bamboo.
7. The bamboo is then stored horizontally in a rain-protected area for 21 to 30 days until it fully dries.

While the boucherie method is ideal for community scale projects, for larger scale treatment it can have limitations. The fact that bamboo must be treated within 24 hours of felling is the primary reason for this. Therefore, the pressure chamber treatment method is an alternative option. Using this method, culms can be treated up to two to three months after felling. The culms, which have holes drilled either side of the nodes to allow entry of the preservative solution, are placed in a pressure chamber where preservative is injected under pressure (Liese and Kumar, 2003). Figure 28 shows a pressure chamber treatment set up.

The pressure chamber treatment method is ideal for large-scale commercial operations. However, the initial start up cost for a unit is considerably higher than for the boucherie method. Furthermore, as bamboo is typically felled after the rainy season when sugar content in sap is lowest (November-January), the operational period of the unit (or the capacity utilization factor - CUF) is approximately 120 days per year (CUF 33%). Therefore, bamboo treatment plants should ideally be incorporated with existing treatment regimes for timber, where these apply, to increase output from the enterprise. However, in Bhutan, timber is not usually treated before being sold on the market (Chhetri and Pradhan, 2013 – personal communication). These factors need to be taken into co nsideration when considering whether to establish such a plant. Given Bhutan's current resource base, community scale treatment methods such as the Boucherie method may represent the most feasible means of treatment at the current time.

Financial Analysis of Bamboo Treatment Technologies

As with plantations in the previous section, we assess the viability of chemical treatment preservation using boucherie and pressure chamber treatment methods. However, as we cannot be certain of the final market price at which treated culms will be sold, we calculated the annualized cost of supplying a treated culm using the two technologies. The annualized cost tells us the actual discounted cost of producing each treated culm over the life of the treatment unit. For all of our calculations for the boucherie treatment method, we take the input price of a bamboo culm at the highest market price found in Bhutan (BTN130) and a projected future sale price of BTN50 for new plantations, consistent with our earlier financial analysis of plantations. Based on the calculated annualized cost, we then set a retail price mark-up to ensure an IRR of 20%. We took this as a rough retail price for final treated culms, which we can use as an approximation to assess projected costs of bamboo vis-à-vis timber for structural applications.

In our calculations for the boucherie method, two types of boucherie kit - manual and electric - are assessed; the manual kit is pumped by hand using a bicycle pump, whereas the electric kit is pumped up to the required pressure using an electronic motor. The manual kits are already in use in Bhutan. It is assumed that manual kits would be predominantly used in Bhutan, but this may change with increased electricity coverage in the future. A list of all the main assumptions used in our calculations for boucherie kits are given below in tables 11 and 12.

ASSUMPTIONS - Manual Boucherie Treatment Unit			
	Rate	**Units**	**Source**
Discount Rate	14%		*SFED*
Project Life	10	*Years*	*ABARI*
Tax and royalties	Not included		
Salvage value at end of project	0	*BTN*	
Bamboo Demand Per Day	60	*Culms/day*	*ABARI*
Number of Days of Utilization Per Year	92	*Days/yr*	
Number of workdays to dry bamboo	20	*Days/yr*	*INBAR*

Capacity Utilisation Factor	25%		
Cost of Raw Bamboo Culms	130 or 50	*BTN/culm*	*SFED*
Water Demand Per Treatment Day	90	*Litres/day*	*ABARI*
Boron Preservative Demand Per Treatment Day	9	*Kg/cycle*	*ABARI*
Unit Cost of Water	0	*BTN/L*	*SFED*
Unit Cost of Boron Compounds	135	*BTN/kg*	*SFED*
Operators (labour)	5	*People*	*ABARI*
Labour Rates			
1. Operators	165	*BTN/day*	*SFED*
Initial Capital Costs			
1. Broucherie Kit	125000	*BTN/unit*	*ABARI*
2.temporary storage sheds	6250	*BTN/unit*	*SFED*
Maintenance costs	4%	*% Fixed costs*	*ABARI*

Table 11: Assumptions used for financial calculations of a manual boucherie treatment unit in Bhutan

ASSUMPTIONS - Manual Boucherie Treatment Unit			
	Rate	**Units**	**Source**
Discount Rate	14%		*SFED*
Project Life	10	*Years*	*ABARI*
Tax and royalties	not included		
Salvage value at end of project	0	*BTN*	
Bamboo Demand Per Day	70	*Culms/day*	*ABARI*
Number of Days of Utilization Per Year	92	*Days/yr*	
Number of workdays to dry bamboo	20	*Days/yr*	*INBAR*
Capacity Utilisation Factor	25%	*Days/yr*	
Cost of Raw Bamboo Culms	130 or 50	*BTN/culm*	*SFED*
Water Demand Per Treatment Day	105	*Litres/day*	*ABARI*
Boron Preservative Demand Per Treatment Day	10.5	*Kg/cycle*	*ABARI*
Unit cost of electricity	1.28	*BTN/kwh*	*Bhutan Power Coorp.*
Unit Cost of Water	0	*BTN/L*	*SFED*
Unit Cost of Boron Compounds	135	*BTN/kg*	*SFED*
Operators (labour)	4	*People*	*ABARI*
Labour Rates			
1. Operators	165	*BTN/day*	*SFED*
Initial Capital Costs			
1. Broucherie Kit	155000	*BTN/unit*	*ABARI*
2.temporary storage sheds	6250	*BTN/unit*	*SFED*
Maintenance costs	5%	*% Fixed costs*	*ABARI*

Table 12: Assumptions used for financial calculations of an electric boucherie treatment unit in Bhutan

For the pressure treatment chamber units, the same methods are applied. However, we assume that the current restricted nature of the resource base would preclude present investment in this treatment technology. Therefore, we only conduct the financial analysis against future projected costs for raw bamboo materials sourced from the expected new plantations introduced in section 4. A list of the assumptions we use for our financial calculations on pressure treatment chamber units are given in table 13 below. It should be noted, as no such facility exists in Bhutan, all prices are taken from a facility in Chitwan, Nepal operated by the Adobe and Bamboo Research Institute (ABARI).

ASSUMPTIONS - Manual Boucherie Treatment Unit

	Rate	Units	Source
Discount Rate	14%		*SFED*
Project Life	20	*Years*	*ABARI*
Bamboo Demand Per Treatment Cycle	80.0	*culms/cycle*	*ABARI*
Number of Treatment Cycles	240	*cycle/yr*	*ABARI*
Capacity Utlisation Factor	33%		
Number of workdays to dry bamboo	80	*days/yr*	*ABARI*
Cost of Raw Bamboo Culms	50.0	*BTN/culm*	*INBAR*
Electricity Demand Per Treatment Cycle	3.0	*kwh/cycle*	*ABARI*
Water Demand Per Treatment Cycle	1000	*litres/cycle*	*ABARI*
Boron Preservative Demand Per Treatment Cycle	40	*kg/cycle*	*ABARI*
Unit Cost of Electricity	1.96	*BTN/Kwh*	*Bhutan Power Corp*
Unit Cost of Water	0.06	*BTN/L*	
Unit Cost of Boron Compounds	135	*BTN/kg*	
Senior Operator Labour Requirements	1	*People*	*ABARI*
Junior Operator Labour Requirements	4	*People*	*ABARI*
Labour Rates			
1. Senior operators	5000	*BTN/month*	*SFED*
2. Junior operator	165	*BTN/day*	*SFED*
Transportation Truck Load Capacity	400	*culms/load*	*ABARI*
Intermediary Truck Cost (inc. manual)	6000	*BTN/load*	*SFED*
Initial Capital Costs			*ABARI*
1. Treatment Chamber	1865000	*BTN/unit*	
2. Shed	626550	*BTN/unit*	
3. Water Storage Tank (7,000L)	62655	*BTN/unit*	
4. 3 Phase Electricity (10KVA)	Available	*BTN/unit*	
5. 10KVA generator	313275	*BTN/unit*	
6. Land	68	*m2*	
7. Hand Drill	12400	*BTN/unit*	
Maintenance costs	3%	*% fixed costs*	*ABARI*

Table 13: Assumptions used for financial calculations of a pressure treatment unit in Bhutan

In table 14 below, we provide a summary of the main findings of our financial analysis for boucherie and pressure chamber treatment units

	Manual Boucherie	Manual Boucherie	Electric Boucherie	Electric Boucherie	High pressure treatment
Price per					
Untreated culm	130	50	130.0	50	50
Annualised cost per treated culm	168.9	88.9	164.9	84.61	159.39
retail price required for 20% IRR	176.7	94	172.3	89.7	174
Discounted cash inflow @ 20% IRR	5331843	2886104	6076549	3226546	25058085
Discounted cash outflow @ 20% IRR	4907589	2604152	5584725	2897382	20899670
Net Present Value @ 20% IRR	424254	281952	491824	329164	4158416
Benefit/Cost ratio @ 20% IRR	1.09	1.11	1.09	1.11	1.2

Table 14: Summary of financial analysis for boucherie & pressure treatment units in Bhutan

Interpretation of Calculations

Importantly, the reader should note that all analysis above excludes taxes and royalty payments. Conversely, we also assume zero salvage value for capital assets at the end of the investment. Based on the analysis, the cost of producing bamboo using the high-pressure treatment method appears considerably higher than for the boucherie method. The annualized cost of BTN159.39 per treated culm, given a raw material culm price of BTN50, for the high-pressure treatment unit is far higher than the equivalent cost of boucherie treatments (BTN88.9-84.61). This is partly indicative of the fact that boucherie treats materials at the source of felling and utilizes them in community construction, thus forgoing the cost of transportation.

From the above estimated prices, in this section, we will now compare the approximate cost of using bamboo in construction versus timber. For this exercise, we will return to our example of the roof truss from section 4. In Table 15 below, the cost of using 1st class mixed conifers in 6m, 8m and 10m length trusses are given. In table 16, based on our estimated costs for treated bamboo, the comparative prices of equivalent bamboo materials for 6m, 8m, and 10m trusses are also provided. The bamboo material rate is calculated based on the most expensive available treatment technology and raw material price (manual boucherie at today's highest bamboo culm price). Assuming a treated culm is roughly 6 meters long, we calculated the meter rate by dividing the culm retail price by 6.

Wood work for trusses	No.	Length	Width	Height	Quantity	Unit	Rate	Amount
For 6m length								
Providing and fixing roof framing in trusses, purlins, rafters, posts, post plates etc the cost of steel items in 1st class mixed conifer, Bottom Chord	1	6.00	0.10	0.12	0.07	m^3		

Rafters	2	3.07	0.10	0.12	0.07			
Vertical Post	1	0.58	0.10	0.12	0.01			
	2	0.28	0.10	0.12	0.01			
					0.16	m^3	19889.18	3169.54
For 8m length								
Providing and fixing roof framing in trusses, purlins, rafters, posts, post plates etc the cost of steel items in 1st class mixed conifer, Bottom Chord	1	8.00	0.10	0.12	0.10	m^3		
Rafters	2	4.10	0.10	0.12	0.10			
Vertical Post	1	0.81	0.10	0.12	0.01			
	2	0.41	0.10	0.12	0.01			
Struts	2	1.69	0.075	0.10	0.03			
					0.24	m^3	19889.18	4759.68
For 10m length								
Providing and fixing roof framing in trusses, purlins, rafters, posts, post plates etc the cost of steel items in 1st class mixed conifer, Bottom Chord	1	10.00	0.10	0.12	0.12	m^3		
Rafters	2	5.12	0.10	0.12	0.12			
Vertical Post	1	1.00	0.10	0.12	0.01			
	2	0.68	0.10	0.12	0.02			
	2	0.35	0.10	0.12	0.01			
Struts	2	1.53	0.075	0.10	0.02			
	2	1.39	0.075	0.10	0.02			
					0.32	m^3	19889.18	6432.16

Table 15: Estimated cost of 1st class conifer timber materials for 6, 8 and 10m length trusses

Note: The above cost estimate is for one roof truss. The quantity of purlins could not be quantified as it depends on the size of building. The rate applied is Bhutan Schedule of Rates - 2012

Wood work for trusses	No.	Length	Diameter	Quantity	Unit	Rate	Amount
For 6m length							
Horizontal Members	1	2.1	0.10	2.1	M		
Rafters	2	4.87	0.10	10			
Diagonal Poles	1	2.5	0.10	2.5			
Cross Bracing	7	1.5	0.10	10.5			
Struts	2	.85	0.10	2			
Wall Plates	2	1.5	0.10	3			
Total Bamboo				19.6	meter	29.45	577.22
Metal Brackets	10	10	10	6		150	900
Total Cost							**1477.22**
For 8m length							
Horizontal Members	1	3	0.10	3	M		
Rafters	2	6	0.10	12			
Diagonal Poles	1	3	0.10	3			
Cross Bracing	7	3	0.10	21			
Struts	2	1	0.10	2	M		
Wall Plates	2	1.5	0.10	3			
Total Bamboo				44	Meters	29.45	1295.8
Brackets	10			10	Nos	150	1500
Total Cost							**2795.8**
For 10m length							
Horizontal Members	1	3.5	0.10	3.5	M		
Rafters	2	7	0.10	14			
Diagonal Poles	1	4	0.10	4			
Cross Bracing	7	4	0.10	28			
Struts	2	1	0.10	2			
Wall Plates	2	1.5	0.10	3			
Total Bamboo				54.5	meter	29.5	1605.03
Metal Brackets	10	10	10	14		150	2100
Total Cost							**3705.03**

Table 16: Estimated cost of bamboo materials in bamboo trusses of 6, 8 and 10m in length

The comparison shows that, even taking the highest typical current price of culms in Bhutan (130BTN), bamboo trusses appear to be roughly half the price of equivalents made from 1st class conifer timber. It should be noted that this analysis only covers the cost of truss building materials, while other costs for items such as labour in truss construction are excluded. Furthermore, no tax or royalty payments have been made on bamboo in our analysis, but these are included in the timber rates. However, despite these points, it still seems likely that bamboo can provide an affordable alternative, especially if raw material prices fall in the future.

Assuming plantations will deliver culm yields of around 1,000 culms/ha a year upon reaching maturity, a community-led boucherie unit, which typically can treat 60 (manual) to 70 (electric) culms a day when running at full capacity, would need a plantation area of roughly 5-6ha.

This suggests that there is already capacity to set up further boucherie treatment units in Dzongkhag, where there is a surplus of bamboo, such as in *Samtse*. Furthermore, if community forestry management groups for bamboo expand in the future, boucherie treatment units could prove a financially viable model for preserving locally harvested bamboo, while, at the same time, increasing value addition for community members.

While boucherie treatment is highly suitable for community projects, for larger scale industry a high-pressure treatment unit may be required. However, given the high initial capital investment and large raw material requirements of such a plant, we advise that these investments should be made at a later stage in Bhutan's sector development. For example, if we again assume that mature plantations will produce yields of roughly 1000 culms/ha, this type of pressure treatment chamber unit would need to be situated in an area adjacent to 19ha of bamboo plantation that has good road access to markets. If the plant were run below maximum capacity, annualized costs of treatment would increase further. In addition to resource availability, the higher cost of transport and large investment necessitate that there are accessible markets for treated bamboo materials in peri-urban and urban areas.

Section 6: Recommendations for Bamboo Construction Sector Development

Based on the results of our study, our overall conclusion is that there is good potential to develop a commodity value chain for bamboo construction in Bhutan. However, without significant improvements to resource base management and development, as well as strengthened capacity to design and build with bamboo, the scale of construction will probably be limited to a restricted, small-scale number of buildings each year. In order to maximize potential of the sector, we have the following suggested recommendations for the Royal Government of Bhutan:

1. Target construction markets for bamboo building components rather than houses

As our feedback on the INBAR-built bamboo demonstration house from the community in *Tingtibi* shows, there are still many negative perceptions of bamboo as a building material among the Bhutanese general public. Therefore, acceptance of whole structures built predominantly from bamboo for residential housing may meet with considerable resistance in the short-to-medium-term. Therefore, we suggest that sector planners should focus their attention on using bamboo in specific applications, such as for roofing, where the material may even be hidden from view if necessary. Other niche markets for structural applications include tourism and horticulture (greenhouses), which may also provide a stimulus for developing viable construction markets. In addition to specific and niche uses, utilization of bamboo in high-profile demonstration structures, such as the Gross National Happiness Center[3], can play an important role in changing perceptions and promoting the material. Emphasis should be given to increasing utilization of the material, which, in turn, will support further innovation and a wider range of applications.

2. Continue to collect more data on the mechanical properties of local bamboo species and improve design protocols

While the current project has started the process of collecting mechanical property data for local bamboo construction species, as well as simplifying designs, a great deal more work is still needed in this area. The current CFC project has funded initial pilot research, but available data is not representative of bamboo populations in Bhutan. As a first step, we recommend that the authorities should expand field tests on bamboo in Bhutan and could use the portable kits described in section 2 of this report to help do this.

Existing ISO standards, ISO 22157-1 & 2, and Section 3B of Part 6 of the Indian Building Code on Structural Design for Bamboo could be used as a reference to collect data on bamboo, with the new INBAR-developed mechanical portable testing kit set-ups helping derive additional property data (EI, BM, and F). During large scale testing, the authorities, with help from INBAR, could review the performance of the portable testing kits and resolve any future technical issues. For example, for beam applications, while in our current test set up we assume that if we keep the maximum value of Δ fixed, then both the values $E*I$, as well as the safe bending moment will be proportional to the measured maximum value W, in reality, this may not be possible in a single span test set up, as some culms (especially in the larger range of diameters) may fail in strength (Chaturvedi 2013).

Having developed a much more robust set of mechanical property data for local bamboo construction species, it will then be possible to further refine design concepts for roofs and columns used in typical housing structures, as featured in section 3 of this report. Other areas that would also need to be assessed over time include fire resistance, as well as creep and deformation rates. This work can then be integrated into the development of official building guidelines, and, ultimately, a chapter in Bhutan's Building Code (see recommendation 3).

[3] The Gross National Happiness Center is already planning to include meditation rooms made with local materials including bamboo (Chhetri, 2013 – personal communication)

3. Develop official guidelines for building with bamboo in Bhutan

In order to set up a functioning value chain for bamboo construction, one of the key priorities for the authorities in Bhutan should be to establish agreed upon guidelines for building with bamboo materials. These could eventually form part of Bhutan's existing building code as a new chapter on bamboo. Such work would provide a much needed reference point for designers and, ideally, should be incorporated into both vocational training and academic courses in Bhutan. This would provide the necessary resources to develop local capacity to construct with bamboo at scale.

One of the key concepts for developing the official guidelines should be that they incorporate traditional building practices with bamboo (i.e. Erka walls) rather than overrule them. Furthermore, for vernacular, low-rise structures in rural settings, rigorous structural design guidelines requiring detailed calculations may prove to be unworkable in practice. Therefore, the guidelines should probably focus on outlining general 'rules of thumb' and include some simple, pre-prepared design drawings. Previous research has shown that for traditional vernacular bamboo buildings, general 'rules of thumb' can provide adequate levels of safety (Janssen 1995 & Janssen 2000).

For more complex or ambitious buildings, designers could refer to existing international ISO standards for bamboo (ISO 22156, 22157-1 and 22157-2) and the Indian Building Code chapter 3B on bamboo. However, it should be adapted for the local context in Bhutan. Designers could also utilize the strength grading practices reported on in section 2 of this study. Therefore, the most important fundamental principle for any formal guideline or code development is that it should ensure safety, while at the same time being practical to implement across a wide span of scenarios, ranging from low-rise vernacular homes in rural areas to more complex structures in urban settings.

As part of this CFC project, INBAR has already produced a draft building guideline for bamboo in Bhutan, which attempts to incorporate the concepts introduced above. This could be used as a reference by the relevant agencies help develop an official bamboo building guideline for Bhutan in the future.

4. Develop an accurate inventory of all bamboo species and set up a National Bamboo Resource Management and Development Plan

In order to properly develop and manage existing resources as well as expand planting areas, we recommend that the Government of Bhutan should undertake a national resource inventory of bamboo species in the country, preferably supported by Remote Sensing and Geographical Information System (GIS) techniques. As part of this process, it would also be useful for SFED to work with partners to develop an identification field manual and build capacity of local extension workers and communities to easily classify bamboos and carry out rapid resource assessment appraisals. If remote sensing studies are feasible, this approach would also enable communities and extension staff working at Dzongkhag Forestry Services (DzFS) and Territorial Divisions (TD) to ground truth remote sensing results. In addition to developing better data to enable the sustainable management of existing resources, inventory mapping could also include identification of degraded areas and steep slope areas unproductive for agriculture, where it would be feasible to expand bamboo production and develop new plantations.

To realize this recommendation, local capacity to manage and propagate bamboo resources will also need to be significantly increased and out-scaled to reach communities and technical extension workers throughout bamboo growing regions of the country. Potential partners for this could include the Renewable Natural Resources (RNR) research system, the College of Natural Resources, Department of Forests and Park Services, and Ugyen Wangchuck Institute for Conservation and Environment (UWICE), which already runs one-year certificate courses in Conservation, Environment and Forestry Studies (CEFS), as well as tailor - made professional courses.

5. Improve bamboo sector planning and coordination to fully implement existing policy frameworks

In relation to the third recommendation, more effort is also needed to effectively coordinate and implement sector development and planning. While our study found that most of the major policy frameworks are in place to support sector growth and development, planning and coordination remains fairly weak. This is evidenced by the NRDCL's lack of awareness of the bamboo priority species list in the national NWFP strategy document, when establishing new recent bamboo plantations in Samtse. Fortunately, the working group on bamboo under the NWFP national strategy already provides an ideal forum for planning and coordinating sector development. However, in order for it to fulfill this purpose, the group must be an active body that meets and communicates regularly. Therefore, it may be advisable to nominate a group secretary within SFED, who is responsible for organizing meetings and networking among group member organisations. Systems of reporting within SFED for this group should also ideally be in place to ensure that prescribed actions are actually being taken.

Group coordination and implementation of policy should also follow an evidence-based approach. SFED has recently set up a Monitoring & Evaluation system that will include NWFPs. It is vital that this action is fast-tracked to assess and guide future implementation of bamboo policy.

Apart from strengthening the existing network of partners, this network should also be expanded in scope to build the multi-sector partnerships necessary to support bamboo sector growth. For example, in order to develop construction markets, it is imperative that the Ministry of Works and Human Settlement becomes involved in bamboo sector planning. Furthermore, within the Department of Forests and Park Services, there is also great scope to extend the number of stakeholders. For example, the Nature Recreation and Eco-tourism Division (NRED) is now tasked with supporting Dzongkhags and national parks to develop tourism infrastructure. NRED is already working with timber and stone masonry, but has no current plans for working with bamboo (Gyeltshen, N., 2013 – Personal Communication). Outside of construction and forestry, SFED should also consider establishing linkages with the Department of Agriculture. For example, as previously mentioned in section 3 of this study, the Horticulture Division now has a programme to subsidize greenhouses for which bamboo could be considered as an option (Dorji, U., 2013 – Personal Communication). Finally, the private sector must be engaged to scale up proven best practices.

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Appendix 1: Interviews Conducted

Chhetri, A. and Pradhan, N., 2013. Personal interview with Ashit Chhetri, Manager, Forest Resource, Natural Resource Development Corporation Limited (NRDCL) and Narayan Pradhan, Division Director, Forest Resource, NRDCL. Conducted in person Thimphu, Bhutan, May 22nd 2013

Chhetri, S., 2013. Personal interview with Dr. Saamdu Chhetri, Director, Gross National Happiness Center. Conducted in person Thimphu, Bhutan, May 24th2013

Dorji, U., 2013. Personal interview with Ugyen Dorji, Programme Coordinator, Horticulture Division, Department of Agriculture. Conducted in person Thimphu, Bhutan, May 23rd 2013

Ghimeray, K.N., 2013. Personal interview with KN Ghimeray, Section Head, Nursery and Plantation Section, Social Forestry and Extension Division, Department of Forest and Park Services. Conducted in person Thimphu, Bhutan, May 22nd and May 23rd 2013

Gyeltshen, N., 2013. Personal interview with Nawang Gyeltshen, Deputy Chief, Nature Recreation and Eco-tourism Division, Department of Forest & Park Services. Conducted in person Thimphu, Bhutan, May 23rd 2013

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Norbu, Y., 2013. Personal interview with Yonten Norbu, CFC Project Officer, Social Forestry and Extension Division, Depart of Forest and Park Services. Conducted in person Thimphu, Bhutan, May 23rd 2013

Rutland, M., 2013.Personal interview with Michael Rutland, Deputy Chief, British Honorary Consul. Conducted in person Thimphu, Bhutan, May 24th2013

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INBAR's member countries

■ Secretariat offices

P. O. Box 100102-86
Beijing 100102, P. R. China

Tel: + 86 10 64706161
Fax: + 86 10 64702166
Email: info@inbar.int
http:// www.inbar.int
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Authors: Oliver Frith, Nripal Adhikary, Sonam Peldon, Prabhat Kr. Mukhia and Gyeltshen Dukpa
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