ZERO ARCTIC

Concepts for carbon-neutral Arctic construction based on tradition

REPORT

2020

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"If we are to continue to grow such contributions, academics, educators, architectural researchers and practitioners will have to continue to break with all types of silo thinking and instead, embrace systems thinking and take onboard the learning conditions recently described by the anthropologist Henrietta Moore - the future learning will not be about the transferability of whole models with known outcomes, but rather about incomplete learning experimentation and collaboration"

Irina Bauman, 2015 Architecture and Resilience Conference UK Welcome

Executive summary

This report presents the results of the project Zero Arctic: Concepts for carbon neutral Arctic construction based on tradition (2018–2020). The main objective of the project was to provide research-based statements for carbon neutral, resilient and sustainable Arctic construction with special reference to tradition, vernacular architecture and collaboration with indigenous communities.

Zero Arctic was a consortium project led by the Ministry of the environment (Finland) together with Crown-Indigenous Relations and Northern Affairs (Canada) and the following partners: Aalto-University (Finland), Livady Architects (Finland), VTT Technical Research Centre of Finland Ltd, Université Laval (Québec, Canada), Hokkaido University (Japan).

The significance of tradition and vernacular architecture is best displayed in preserved examples of buildings that have had a service life of centuries. They form a source of knowledge of structural and material innovations that can be evaluated and used in modern buildings. The methodological novelty of the project was to unite architectural-historical and Life Cycle Assessment approaches to develop concepts that would be sustainable and carbon neutral at the same time.

The project was based on three case studies in Finland, Canada and Japan. Each case study consisted of a survey of the traditional Arctic dwellings, of structural solutions and settlements, and of a review of the energy consumption of the existing building stock. In the Canadian and Finnish case studies, a prototype building was designed and assessed.

The carbon neutrality target was reached in the Finnish wooden case buildings, and the Canadian cases came very close with 98% reduction of GHG emissions in a case building with high energy efficiency and aggressive use of solar panels.

According to the Finnish assessment, the best suggested solution for Arctic conditions would be wood construction with the utilization of wind and geothermal energy for the building operation. Should the wooden materials be reused in subsequent buildings, carbon emissions from wooden material incineration are not realized and the biogenic carbon content from wooden based materials is extended to the next building case.

The central outcome of the project was the widened awareness of the importance of understanding the locality of traditions and cultural aspects of living when designing sustainable buildings in Arctic regions.

According to the results of the project, we suggest the following recommendations for policy-makers for present and future Arctic construction.

1. When considering sustainability of buildings, the focus should be on the full life cycle impacts.

2. Optimal energy efficiency target should be set for new buildings. Energy efficiency, though an important metric, should never be pursued at the expense of potential service life or air quality.

3. Renewable energy should be included in the micro-grid mix.

4. Lightweight, low-carbon materials, such as wood from sustainably grown forests, should be preferred.

5. The buildings should be designed to enable deconstruction (Design-for-deconstruction), reassembly and reuse.

6. The buildings should be designed for climate resilience. Adjustability and easy maintenance should be pursued as a response to changing weather conditions.

7. Sensitivity towards cultural differences and the recognition of one's culturally related assumptions are key in the prevention of building design solutions that unintentionally modify the culture of its inhabitants.

1.INTRODUCTION

Background

Arctic climate warming is proving to be amplified, non-linear and rapid. Climate modelling timelines are being overtaken by actual pace-of-change events. Evidence based information identifies that under current policies Earth is on track to pass the lower agreed 2015 Paris Accord global average temperature rise of +1.5ºC in 2035 and the higher +2.0ºC target in 2053.[1,2]

Current Arctic temperatures are rising at a rate two to three times the global average. Arctic weather patterns are changing much faster than expected with recent climate warming events beginning to have a profound impact on the lives of the Arctic people.

The built environment, and the ways it is constructed and maintained, has an essential effect on climate and the use of natural resources. Construction and the built environment consume half of all global raw materials, use up to 40% of all primary energy, 30% of all fresh water and cause over 30% of greenhouse gas emissions.[3]

The future of building in the Arctic is thus faced with two distinct challenges. In addition to mitigating climate change through a lowered carbon footprint, the Arctic built environment must also develop a resilience to the new and ever-changing conditions brought by the effects of climate change such as melting permafrost and increased rainfall.

While several of the UN's Sustainable Development Goals (SDGs) are related to the built environment, based on literature review and expert interviews, it is evident that the topic of construction has not been studied as thoroughly as many other topics relating to Arctic sustainability. The urgency of the topic of Arctic construction is only accelerated by the fact that people in Nordic regions spend on average 90% of their time indoors making them especially vulnerable to health risks caused by indoor air quality. The quality of indoor environments has great effects on human well-being especially during seasons of little or no daylight. The impacts of moisture, material and maintenance related problems are both social and economic.

The on-going Covid-19 epidemic has served as a profound lesson on the effects of a global crisis, revealing how unevenly it can distribute its effects among different communities of the world. Circumstantially the Arctic communities' find themselves in a vulnerable position against the effects of both the climate change and Covid-19 crisis.

Since the beginning of the 20th century, Arctic construction has adopted modern technology and standards of living. Especially in the Arctic region, construction may lead to exceptionally high energy consumption due to long transportation distances of building materials, extreme cold winter conditions, problems in the use of some renewable energy technologies, risks for short service life because of harsh environment and the low recycling potential of the building materials in the end of the life cycles of buildings.

Traditional and vernacular architecture provide information on local and global solutions that Arctic cultures have developed to adapt to varying local climates and resources for thousands of years. Therefore, vernacular architecture contains a wealth of knowledge on a global scale that can be applied to solve present-day problems of sustainability. In the Nordic context, the potential of traditional solutions and the need for more research on the field has been recently emphasised in the CERCMA report.[4] In addition, recent studies in Norway indicate that it may take decades for a new building before the initial construction-phase emissions are outweighed by the lower operational

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[1] Special Report on +1.5C [IPCC SR1.5] 2018

[2] UN Secretary General, 2019 Climate Action Summit

[3] UNEP 2017. Global status report 2017. Towards a zero-emission, efficient and resilient buildings and construction sector. https://www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf

[4] *CERCMA - Cultural Environment as Resource in Climate Change Mitigation and Adaptation.* Nordic Council of Ministers. Nordic Working Papers, 2014. https://www.norden.org/en/publication/cercma-cultural-environment-resource

energy use.[5] This throws into relief the problem of short economic and functional service lives of buildings and the possibilities of a circular economy of building components and materials.[6] Here, the tradition opens up an archive of knowledge that may be turned into constructional and operational innovations that meet modern standards of living.

The advancement of sustainable construction in Arctic regions requires an Arctic approach. The project Zero Arctic – Carbon Neutral Arctic building is an endeavour to fill this gap of knowledge, or at least take the critical first steps. The 2-year project was launched in 2018 and works under the Arctic Council and its Sustainable Development Working Group. The project is led by Finland and Canada, with studies also from Hokkaido, Japan, where buildings also face similar challenges to Arctic regions.

The key task of Zero Arctic is to provide research-based understanding and approach in order to understand how traditional and vernacular processes and building materials may be turned into modern innovations and solutions that could mitigate the energy consumption, resource use and associated greenhouse gas emissions in future Arctic construction. In this report, our central outcomes are case-study buildings and assessments for Arctic regions in Finland, Japan and Canada, where traditional materials and construction meet modern standards of living.

The focus of the Zero Arctic project is to develop regional concepts for Arctic building construction that would be carbon neutral over their full life cycle. This is achieved by utilizing both scientific life cycle assessment and energy simulation methods as well as learning from and applying traditional knowledge of sustainable construction. By doing this, the work aims to fill knowledge gaps and to make a science-based statement for policy-makers about how we should build in Arctic districts within the targets of the Paris Agreement and the warming scenario of 1.5°C. Moreover, the work proposes carbon neutral solutions that are sustainable from the angles of service life, recycling, resource efficiency and non-toxic building materials.

In short, the overall objective of Zero Arctic is to examine traditional Arctic buildings to develop and assess Greenhouse Gas (GhG) neutral solutions for Arctic construction.

Out of the three pillars of sustainability, the study focuses on that of environment and of social equality, leaving the pillar of economy for possible future research.[7] Aspects of economy, though potentially very interesting, could not be included within the confines of the study.

THE MORE SPECIFIC OBJECTIVES OF THE PROJECT ARE:

- **to identify the common climatic and geographic factors and phenomena that characterize the Arctic districts and affect the potential sustainable and GHG neutral solutions**
- **to explore the traditional Arctic construction through three case studies concerning Japan (Hokkaido), Canada and Finland**
- **to identify the common factors of traditional Arctic construction that may have an impact on the sustainability and carbon-neutrality of Arctic building**
- **the development of an assessment method for assessing GHG emissions from building in Arctic districts**
- **to design and assess type buildings that fulfill the functional requirements of modern living comfort, learning from traditional knowledge and perspectives**
- **to discuss, through the example of Arctic construction, the possible and potential contribution of traditional construction, building life cycles, environmental adaptation and the use of resources to present-day and future construction**
- **to discuss the results of the assessment and examine unquantifiable factors**
- **to formulate recommendations for policy makers for carbon neutral and resource-wise solutions of construction in different kinds of Arctic districts**

The three Arctic areas and indigenous peoples covered in this study are not identical despite their apparent similarities. For this reason, the evidence and solutions presented, while over-lapping, also vary from country to country. Their is also variance in regional and national ways of calculating and compliling statistics. This information is never objective or apart of cultural and local understandings. The plurality of Artic cases aims to rather provide a broadened perspective of various challenges in the Arctic than to provide a scientific comparison of the Arctic areas in question.

The report is intended for policy makers and researchers of traditional and modern Arctic construction. However, it is at the same time written and illustrated to meet also the needs of a wider audience, since private construction is an important part of the construction sector in the Arctic.

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[5] Berg, Fredrik & Fulgseth, Mie, 2018. "Life cycle assessment and historic buildings: energy-efficiency refurbishment versus new construction in Norway", Architectural Conservation 24, 152–169.

[6] Huuhka, Satu & Lahdensivu, Jukka 2016. "A statistical and geographical study of demolished buildings", Buildings Research and Information 44, 73–96.

[7] Strategic Framework 2017 of SDWG

Traditional buildings as a source of knowledge

Since the 1990s, a wealth of literature has addressed the issue of applying the principles of vernacular architecture to introduce sustainable solutions in contemporary building.[8] A commonly shared standpoint is that vernacular architecture forms a source of knowledge to resource-wise, energy-efficient and sustainable ways to organize human dwellings and settlements. The tradition forms a large warehouse of know-how, it provides testimony of millennia of successful and unsuccessful examples to build and use buildings efficiently and in a resource-wise manner.

Integrating vernacular solutions into the processes of industrial technology is generally not a straightforward task.

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[8] The most comprehensive volume about vernacular solutions, see: Oliver, P. Encyclopaedia of Vernacular Architecture of the World. Cambridge, Cambridge University Press 1997; for case-studies and reviews on applying vernacular solutions to modern construction, see e. g. Afshar, F. & Norton, J. 1997. Developmental. In Oliver, P. (ed.). Encyclopaedia of Vernacular Architecture of the World. Cambridge, Cambridge University Press, pp. 25–27; Rapoport, Amos 2006. Vernacular design as a model system. In Asquith, L. & Vellinga , M. (eds). Vernacular Architecture in the Twenty-First Century. Theory, education and practice. Taylor & Francis, London & New York. 179–198; Ford, J., Martinez, D., 2000. Traditional ecological knowledge, ecosystem science and environmental management. Ecol. Appl. 10 (5); Rashid, M. & Ara, D. R. 2015. Modernity in Tradition: Reflections on building design and technology in the Asian vernacular. Frontiers of Architectural Research 2015, pp. 46–55; Dayaratne, Ranjuth 2018. Toward sustainable development: Lessons from vernacular settlements of Sri Lanka. Frontiers of Architectural Research 2018, pp. 334–346.

VERNACULAR ARCHITECTURE AND TRADITION

There have been relatively numerous attempts to define 'vernacular architecture'. Derived from the latin word vernaculus, meaning indigenous, the concept covers an immense range of different building materials, functions and social contexts. In this report, we use the concept of 'tradition' that also incorporates the knowledge and the cultural, symbolic and social dimensions of the use of buildings. It is neither possible nor purposeful to set a timeframe for the disconnection of traditional and non-traditional construction in the arctic (or globally). In some Arctic regions indigenous architecture is still in use, while in most of the Arctic regions it has been extinct at least for decades. Furthermore, a much more difficult question is to define the boundary of a 'traditional' and a 'non-traditional' building, because the transition has also produced hybrids where both are present (for example post-WWII "Rintamamiestalo" (veteran's house) in Finland).

In this rather technically and pragmatically oriented study, we define traditional construction according to two factors, which are 1) the use of local materials and manual processing and 2) knowledge from previous generations in the local cultural circumstances and social interaction.

RESIDENTIAL BUILDING

'Residential building' is a relatively modern concept and did not emerge in the English language until the 1910s.[1] Where modern (and especially urban) dwellings offer unambiguous examples of buildings that contain 'residential' and/or 'non-residential' spaces, this division is not self-evident in historical and traditional contexts. Changes in building types and spaces for some activities, for example the storage of food, lead to the question of what functions and activities in a building should be considered 'residential'. Also, the culturally constructed and changing conventions that allow some animals to live in the human residential spaces (at present dogs, cats) and have separate precincts for others illustrates the problematics of creating a universal definition for 'residential' spaces or buildings.

In the context of this project, it is not purposeful to make definitions or restrictions based on modern technology or concepts. Therefore, to achieve a systematic picture of the traditional residential system based on various livelihoods of the arctic region, it is arguable to include all the buildings and precincts of dwellings or settlements into the analysis, including unheated storehouses and all built environments.

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[1] Google Ngram viewer.

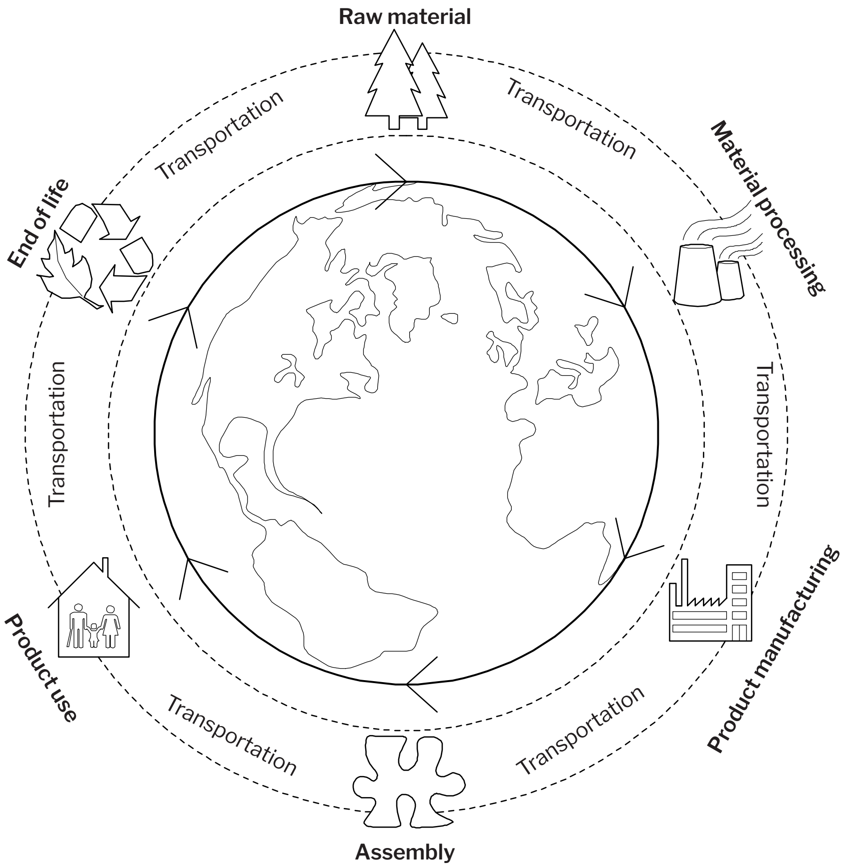

Figure 1. Life cycle assessment. *Livady.*

Besides the technological aspects, there is an immense socio-cultural barrier between the ‘modern’ and the ‘traditional’. Vernacular building techniques and dwellings are often appreciated as cultural heritage or in picturesque and historicised contexts, but seldom conceived as sources of innovation for modern construction. Sometimes tradition is even labeled as ‘primitive’ and ‘indigenous’ otherness, that is considered invaluable for modern construction.

As previously emphasized by Amos Rapoport, among others, integrating vernacular architecture and knowledge into contemporary architecture still lacks a processual, integrative and critical field of research.[9] Instead of romanticising the ‘traditional’ and simply implementing physical features of the vernacular examples to modern construction, the aspects of sustainability should be studied more analytically. This means, as crystallised by Lindsay Asquith and Marcel Vellinga, “to rid the vernacular of its ‘thatched cottage and mud hut’ image”, and “find out how the accumulated knowledge, skills and experience of the world’s vernacular builders may be fruitfully applied in a modern context”.[10]

One of the central questions is indoor environment and thermal comfort. It is essential to understand that traditional solutions without complex building technology or synthetic, highly processed materials, may, in some cases, lead to better performance, what comes to i. e. solid structures, wooden hygroscopic surfaces and indoor quality.[11]

Despite the relatively numerous publications on vernacular architecture and sustainability, only an extremely small amount of research has concentrated on Arctic buildings.[12] Therefore the report contains a concise presentation of vernacular architecture in the Arctic. Finally, the more general purpose of the study is to contribute to the academic, governmental and public discussion on the role of traditional knowledge in developing sustainable solutions. The harsh climate and scarce resources make the Arctic the most challenging permanently populated region on earth. Thus, traditional solutions of Arctic building and living provide an illustrative example of adaptation and creativity and use of local and scarce resources also in the global perspective.

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[9] Rapoport 2006, Vernacular design as a model system.

[10] Asquith, Lindsay & Vellinga, Marcel (eds) 2006. Vernacular Architecture in the Twenty-First Century. Theory, education and practice. Taylor & Francis, London & New York, p. 20.

[11] See chapters 5 and 8 of the report.

[12] Nilsson, Per Olov, 2011. Rökstugan på Mattila. Falun. *** NTNU, CERCMA ***

Life cycle assessment

Life cycle assessment, LCA, is based on a philosophy that considers all environmental impacts through a product's life from extraction of raw materials to disposal.[13]

The International Standardization Organization (ISO) has defined basic principles for life cycle assessment. Life cycle assessment (LCA) compiles and evaluates the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Life cycle inventory analysis (LCI) is one phase of a life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle. LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave).[14]

This study follows the basic principles of life cycle assessment as defined by ISO and EN standards. It focuses on the assessment principles of greenhouse gas emissions. However, when developing recommendations for carbon neutral building in the Arctic region, the study also considers the aspects of indoor environment and comfort and the building-related aspects of cultural heritage.

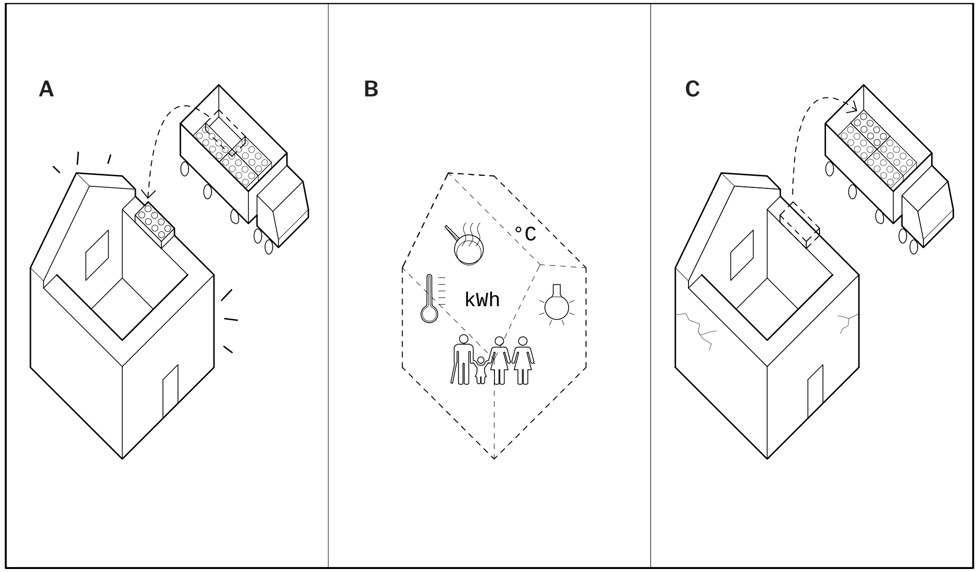

Figure 2. The methodology of LCA at a glance (as a figure). *Livady.*

ISO has also defined more detailed requirements for the environmental and sustainability assessment and declaration of buildings.[15] The method used to asses the environmental performance of buildings in the Finnish case study is specified in the standard EN 15978. The standard presents system boundaries for the building assessment, life cycle stages, list of indicators and indicator calculation methods, and data requirements. This work follows the basic principles of life cycle assessment as defined by ISO and EN as described in Section 1. Based on the climatic and geographic aspects for Arctic districts (see chapter 3), this work emphasises certain issues when defining a method for the GHGs assessment of Arctic buildings:

Although the assessment follows the principles of life cycle assessment, the assessment method focuses on

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[13] Figure from IMPAWATT project Factsheet "What is life cycle management" https://www.impawatt.com/

[14] ISO 14040: 2006. Environmental management — Life cycle assessment — Principles and framework

[15] ISO 21929 Part 1 Sustainability in building construction - sustainability indicators Part 1 Framework for the development of indicators and a core set of indicators
ISO 21931 Part 1 Sustainability in building construction - framework for methods of assessment of the environmental performance of construction works - Buildings
ISO 21930 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services.

the phases of construction, operation and use rather than end-of-life phases (demolition, waste processes, and disposal); end phase scenarios and long service life are discussed, because they form an important part of the life cycle but are mostly difficult to quantify and/or predict.

The assessment method considers both embodied and operational GHG emissions. When assessing the operational impacts, we have chosen a relatively short reference study period (compared to the overall potential service life of buildings). This is because of two reasons: 1) A long assessment timespan decreases the effect of material choices and embodied emissions. The GHG values for energy units will not remain the same as today but the differences will be significant in following decades, because countries aim at abandoning the use of coal in energy supply; 2) The urgency of the climate crisis calls for rapit actions and measures.

Although the basic assessment method focuses on buildings, it allows the assessment on the scale of building groups and consideration of district scale solutions for renewable energy supply.

When assessing net and nearly zero-carbon solutions, the method allows the consideration of seasonal consumption and surplus of energy.

When formulating recommendations for carbon-neutral Arctic buildings, this study emphasizes good energy-efficiency and advanced solutions for renewable energy considering the local potentials, while paying attention to the traditional ways of construction and good indoor environment. The work also recognizes risks of moisture and considers the effect of thermal mass for energy-efficiency.

The definitions of Arctic region(s)

There are several definitions of the Arctic region. Geographically it means areas north of the Arctic Circle. The Arctic Circle is the parallel of latitude that runs 66.56083 degrees north of the Equator (in 2000). All regions north of this circle are known as the Arctic.[16] The Arctic Circle determines the southern extremity of the polar day (24 hours of daylight) in June and the polar night (24 hours of no daylight) in December. Within the Arctic Circle, the Sun is above the horizon for 24 continuous hours at least once per year and below the horizon for at least 24 continuous hours. For example, in Finland, the Arctic region is the northern part of the Province of Lapland above the Arctic Circle. In the natural sciences, this area is called the subarctic region.[17]

However, the oceanic currents and coastal and continental climate factors affect Arctic climates. Thus, the Arctic consists of four different climatic regions, where the flora and fauna (and also the livelihoods and vernacular architecture) differ remarkably:

- Frozen Arctic Ocean and the glacier of Greenland
- Coastal areas and islands with marine climates
- Tundra with permafrost without forests
- Taiga or Boreal Forest

The average temperature in July is an important environmental and biological indicator of ‘northernness’ as an average temperature of 10°C (the 10°C July isotherm) closely corresponds to the timberline. The 10°C-July-isotherm is often used by biologists as a definitional boundary between the tundra and the taiga or boreal forest. The timberline - the line beyond which there are no significant forests or woodlands of coniferous trees - typically formulates the boundary between the two zones. Coniferous woodlands seldom extend into regions in which the mean (average) temperature for the whole of the warmest month of the year is less than 10°C.[18] On the basis of Könnig-Geiger climate zones definitions, the Arctic district belong to Subarctic climate and tundra (“Figure 3: Climate zones”).[19] The word Tundra, which comes from the Sámi word meaning “barren land”, refers to a treeless Arctic region characterized by permafrost.

Roughly 40% (13.4 million km^2) of Arctic districts are land areas and correspondingly 60% are water bodies (roughly 20 million km^2)[20]. The states with districts located north from the Arctic circle are Canada, the United States, Russia, Finland, Sweden, Norway, Greenland (Denmark), Iceland and the Faroe Islands.

The bedrock of the land varies between the old rock formations of Canada, Greenland and Fennoscandia to younger sedimentary rocks and volcanically active areas in Iceland, Jan Mayen and the Aleutians island. Much of the ice-covered areas are in the perch.

The Fennoscandian – Finland, Sweden and Norway and the Kola Peninsula – Subarctic climate is affected by the atmospheric western currents and the warm Gulf Stream branch of the North Atlantic. Because of the mild climate, large areas are covered by a northern coniferous forests or transient zones between forest and tundra. The area is also characterized by the large proportion of lakes. The Northern Boreal coniferous forest is the prevailing vegetation type in Finland (50,000 km^2), while bald areas represent about 16% (15,500 km^2) and swamps roughly 34%.[21]

Arctic areas are inhabited approximately by four million people according to the AHDR (Arctic Human Development Report) definition of the Arctic.

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[16] https://www.britannica.com/place/Arctic#ref518847

[17] https://www.arcticcentre.org/EN/communications/arcticregion

[18] https://research.uarctic.org/resources/atlas/defining-the-arctic/arctic-as-defined-by-temperature/

[19] Geiger, Rudolf (1954). “Klassifikation der Klimate nach W. Köppen” [Classification of climates after W. Köppen]. Landolt-Börnstein – Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, alte Serie. Berlin: Springer. 3. pp. 603–607.

[20] https://fi.wikipedia.org/wiki/Arktis

[21] https://fi.wikipedia.org/wiki/Arktis

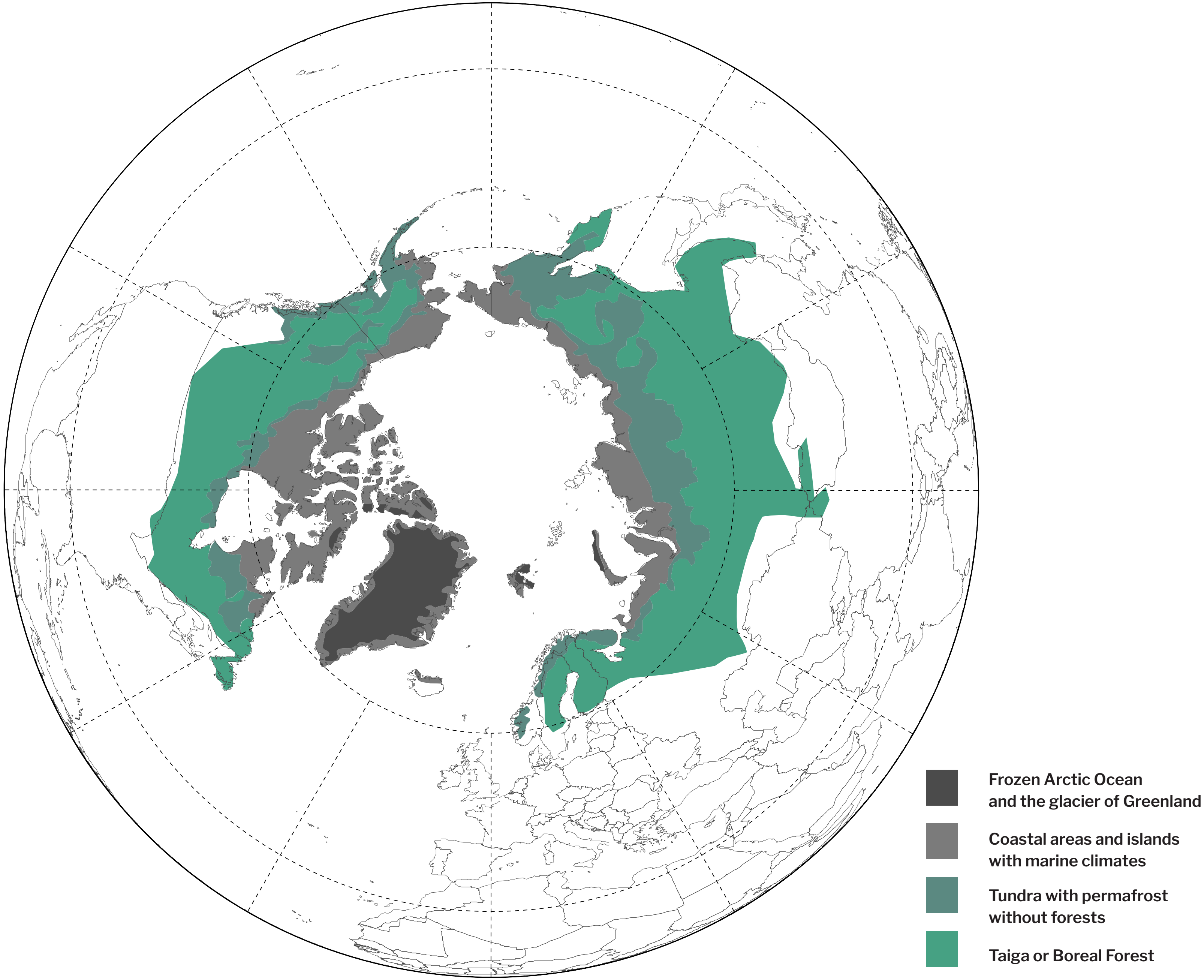
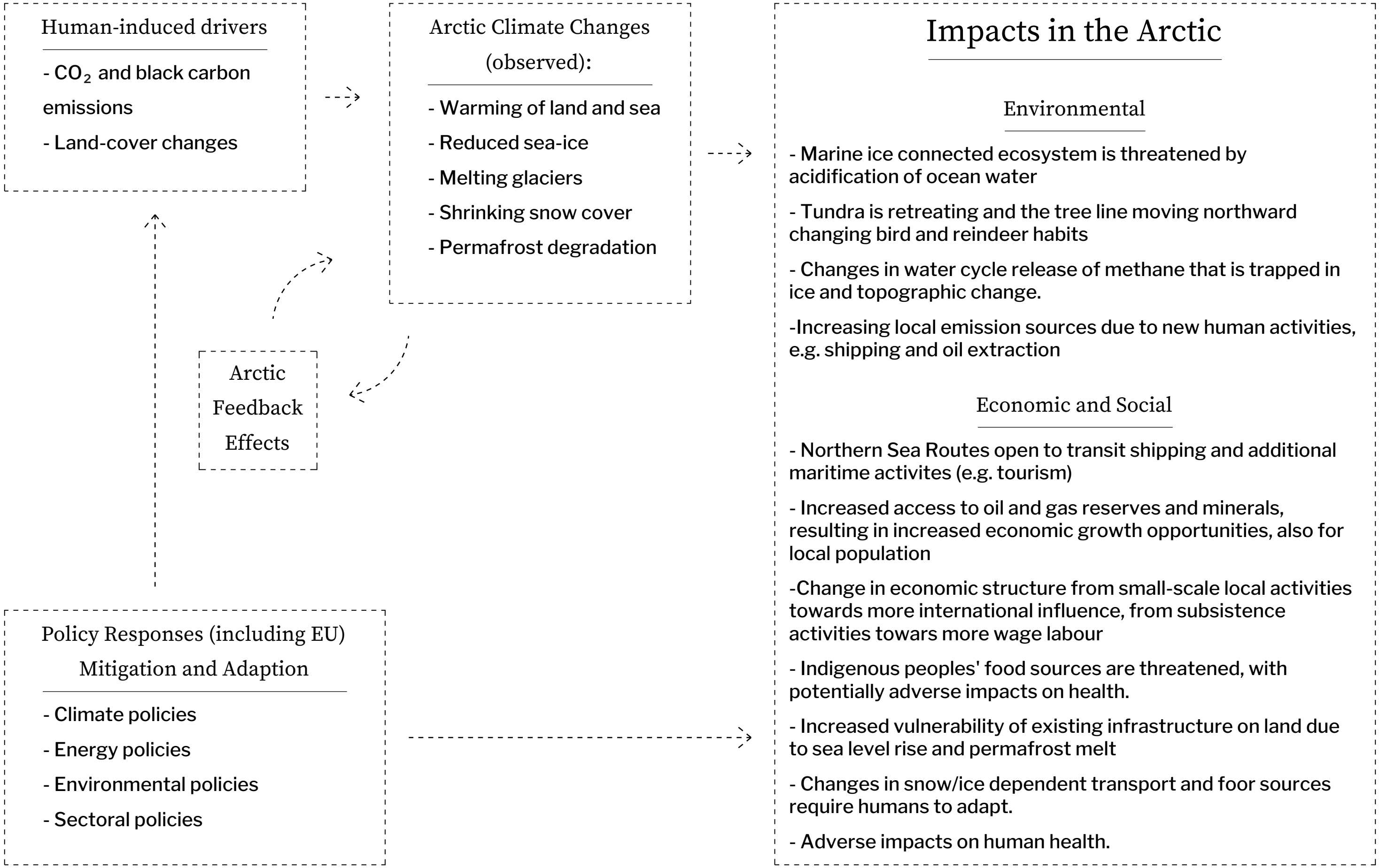


Figure 3. Climate zones. *Livady.*

The settlement area stretches over eight Arctic countries; Canada, United States, Russia, Finland, Sweden, Norway, Iceland and Denmark. The circumpolar region is extremely sparsely populated. With the broader definition of the Arctic by the University of the Arctic Atlas, there are approximately 13.1 million people living in the area of the circumpolar North.

During the 1950s and 1960s, the number of Arctic people started to grow rapidly because of improved health care for indigenous populations and the discovery of vast natural resources located in the North, which led to a large influx of immigrants. Recently, population growth in the Arctic has slowed down in general and in some cases (e.g. Russian North), the total population has been even declining. It is estimated that two thirds of the total population live in relatively large settlements. Settlements of indigenous people living in circumpolar countries are characterized by small, widely scattered communities.[22]

The cultures in the region and of Arctic indigenous peoples have adapted to its cold and extreme conditions. The Arctic region is in a key position from the perspective of the physical, chemical and biological balance in the world.



Human-induced drivers

- CO_2 and black carbon emissions
- Land-cover changes

Arctic Climate Changes (observed):

- Warming of land and sea
- Reduced sea-ice
- Melting glaciers
- Shrinking snow cover
- Permafrost degradation

Arctic Feedback Effects

Policy Responses (including EU) Mitigation and Adaption

- Climate policies
- Energy policies
- Environmental policies
- Sectoral policies

Impacts in the Arctic

Environmental

- Marine ice connected ecosystem is threatened by acidification of ocean water
- Tundra is retreating and the tree line moving northward changing bird and reindeer habits
- Changes in water cycle release of methane that is trapped in ice and topographic change.
-Increasing local emission sources due to new human activities, e.g. shipping and oil extraction

Economic and Social

- Northern Sea Routes open to transit shipping and additional maritime activites (e.g. tourism)
- Increased access to oil and gas reserves and minerals, resulting in increased economic growth opportunities, also for local population
-Change in economic structure from small-scale local activities towards more international influence, from subsistence activities towars more wage labour
- Indigenous peoples' food sources are threatened, with potentially adverse impacts on health.
- Increased vulnerability of existing infrastructure on land due to sea level rise and permafrost melt
- Changes in snow/ice dependent transport and foor sources require humans to adapt.
- Adverse impacts on human health.

Figure 4. Climate in the Arctic – Impacts and Drivers.

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[22] https://www.arcticcentre.org/EN/communications/arcticregion

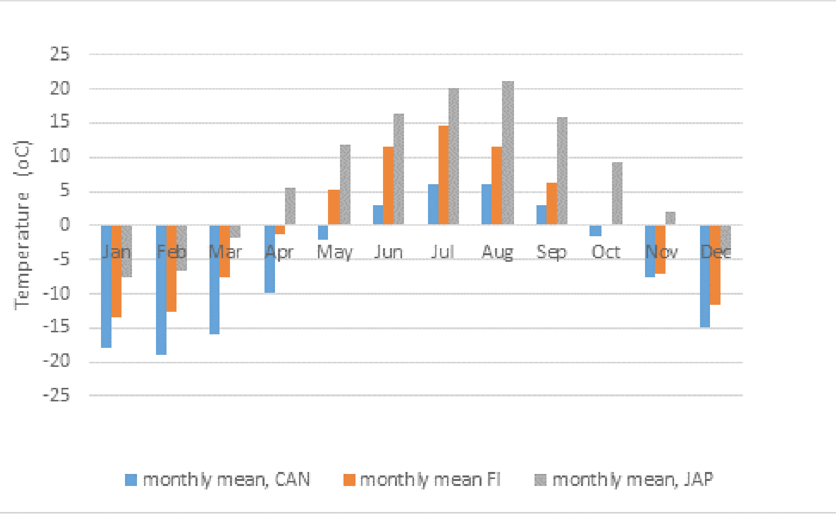

Figure 5. Comparison of current annual temperature in °C(Canada – Quataq, Finland-Sodankylä, Japani - Asahikawa).

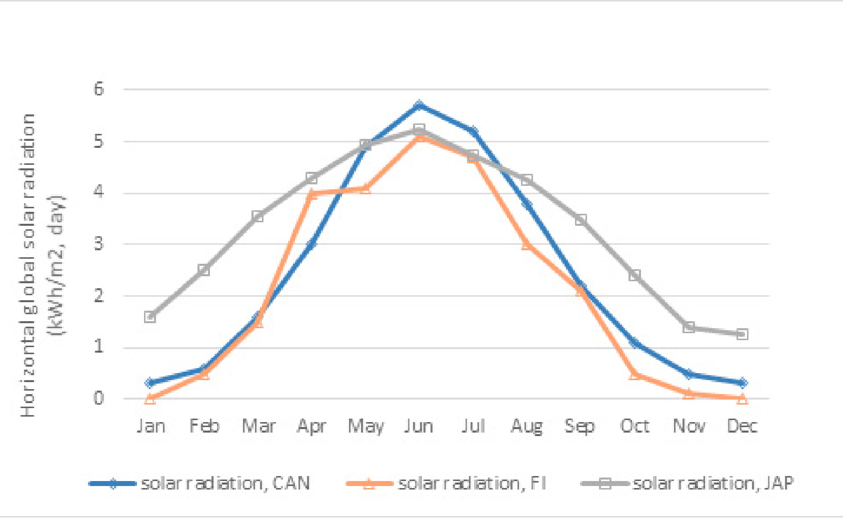

Figure 6. Comparison of current annual horizontal global solar radiation in kWh/m^2, day (Canada – Quataq, Finland- Sodankylä, Japani - Asahikawa).

The Arctic is quick to react to changes in the climate, which reflect extensively back on the global state of the environment. Within climate change research, the Arctic region is considered a so-called-early warning system.[23]

The Arctic is the most rapidly changing climate region on Earth. There is clear evidence of change that has already occurred due to human activities. These affect the fundamentals of Arctic ecosystems and the lives of Arctic peoples. The Arctic is a particularly fragile region where strong ecosystem feedbacks accelerate changes compared with other regions; an effect called "Arctic amplification". Extreme warming through amplification is affecting all year round temperatures. On a number of occasions since December 2015, North Pole midwinter temperatures have risen +25^{0}C within a twenty four hour period. Examples of record Arctic summer highs matching southern European temperatures are being recorded. It is anticipated that this region will be rain dominated - not snow dominated - by the 2030s.[24]

Changes in the Arctic ecosystem dynamics have global consequences.[25] The consequences will include rising sea levels, changes in climate and precipitation patterns, increasing severe weather events, and loss of fish stocks, birds and marine mammals as claimed by WWF.[26] People will directly feel the effects of change as permafrost melts, sea ice disappears and as the circumstances for some of the traditional life style of liv-

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23 What is the Arctic region? https://www.arcticcentre.org/FI/arktinenalue

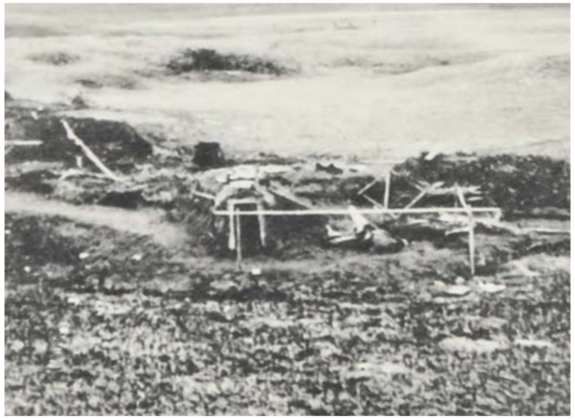
24 Lynas 2020 Our Final Warning

25 https://www.arcticinfo.eu/en/eu-arctic-impact-assessment-factsheets-climate-change

26 https://arcticwwf.org/work/climate/

Sámi *goahti*

Inuvialuit *igluryac*



Ainu *Toi-Chise*

ing is threatened.[27]

There is no typical "Arctic" anywhere, but there are different regions with relatively different environmental, social, political and cultural conditions.

However, there are specific features that typically characterise Arctic districts as listed in the following. Many of these significantly affect the ways of building and construction and also the potential solutions for carbon neutral building.

In terms of vernacular architecture, there are no well-established definitions for 'Arctic construction' or 'Arctic vernacular architecture'. In this project, the concept of Arctic includes both Arctic and Sub-arctic areas, where one of the key factors are nomadic or hunter-gatherer livelihoods, except for the Nordic countries, where also cultivation extends to the (geographically defined) Arctic region.

To provide an overall scope of Arctic circumstances, the case studies of this research project were chosen from different regions of the northern hemisphere. Nordic countries, Eastern Canada and Hokkaido represent different ways humans have adopted to Arctic climate in varying climates and availability of resources.

CHARACTERISTICS OF ARCTIC DISTRICTS:

- **seasonal variations in daylight hours**
- **sparsely inhabited**
- **windiness in many regions**
- **potentially high snow loads and icing of structures**
- **permafrost or seasonally frozen ground**
- **the most rapidly changing climate**

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[27] http://www.cambridgeblog.org/2016/07/how-is-climate-change-affecting-polar-regions-part–1-professor-david-walton/

2. CLIMATE AND POPULATION

(of Finland, Canada and Japan)

Finland

Arctic Finland is located in Northern Finland between the Arctic Circle and 70 degrees latitude north. The climatic and biomic conditions are subarctic, characterized by boreal taiga, cold winters and mild summers. The oldest archaeological testimony of human permanent settlements dates[28] back to the post-glacial era ca. 8 000 BC.

Northern Arctic Finland contains four municipalities: Inari, Enontekiö, Utsjoki and Sodankylä with a population of 18 297 inhabitants (Table 1). In total this region of Arctic Finland includes 20% of the Sámi population (Table 2). The majority of this population is between the ages of 15 – 64 (Figure 8b). According to recent estimates, the total population will decrease approximately 3% per every ten years (Figure 8a) in Arctic Municipalities of Finland and the only Sàmi demographic that is estimated to increase is that of people aged over 66 (Figure 8 b).

The Sámi are the indigenous people of Finland. They are the only indigenous people in the European Union that have a common history, tradition, lifestyle and community. The status of the Sámi was written into the Constitution of Finland in 1995 and the Sámi have constitutional self-government in the Sámi Homeland in the spheres of language and culture since 1996. This self-government is managed by the Sámi Parliament established by law.

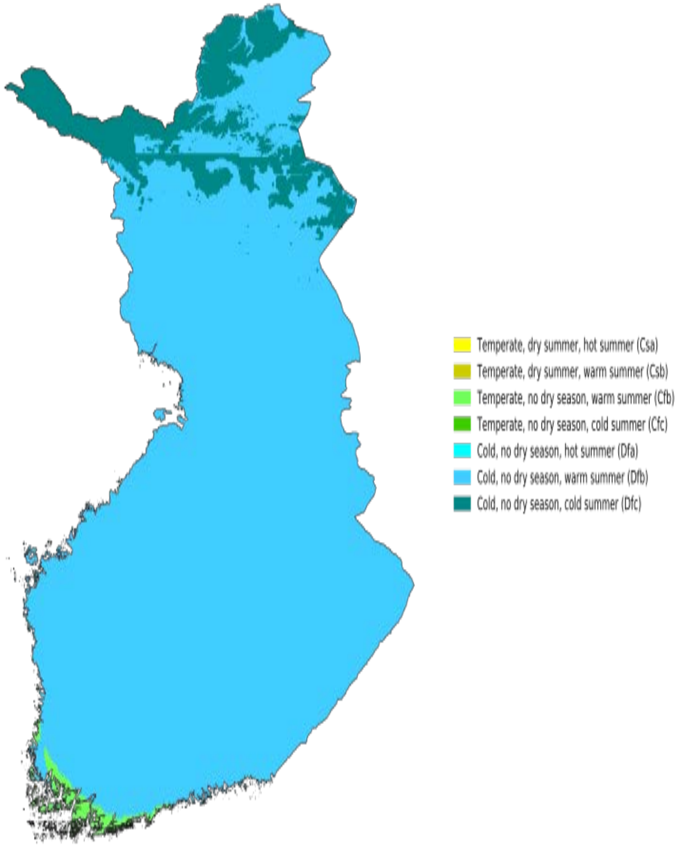

Figure 7. Köppen-Geiger climate classification map for Finland.
Present and future Köppen-Geiger climate classification maps at 1-km resolution". Nature Scientific Data.: Beck, H.E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F

Procedures exist for seeking the free, prior, and informed consent of the Sámi from the Sámi Parliament in Finland for research projects dealing with Sámi cultural heritage and traditional knowledge and other activities that have or may have an impact on this heritage and knowledge.

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[28] Ojanlatva, Eija, 2013. "Mitä on saamelaisalueen arkeologinen kulttuuriperintö", teoksessa Magga, Päivi & Ojanlatva, Eija (toim.), *Ealli Biras – Elävä ympäristö. Saamelainen kulttuuriympäristöohjelma*. Saamelaismuseosäätiö, Inari, 41.

	Population forecast (all inhabitants)		
Municipality\ year	2020	2030	2040
Inari	6 988	7 197	7 234
Enontekiö	1 849	1 842	1 786
Utsjoki	1 221	1 175	1 150
Sodankylä	8 239	7 577	7 017
Total	18 297	17 791	17 187

Table 1. Population forecast for Arctic Municipalities, Finland (Inari, Enontekiö, Utsjoki, Sodankylä).

Municipality	%	
Inari	30%	of the Inari population
Enontekiö	19%	of the Enontekiö population
Utsjoki	70%	of the Utsjoki population
Sodankylä	4%	of the Sodankylä population
Total	20%	of the total population above

Table 2. Share of Sámi in the total population by municipality.

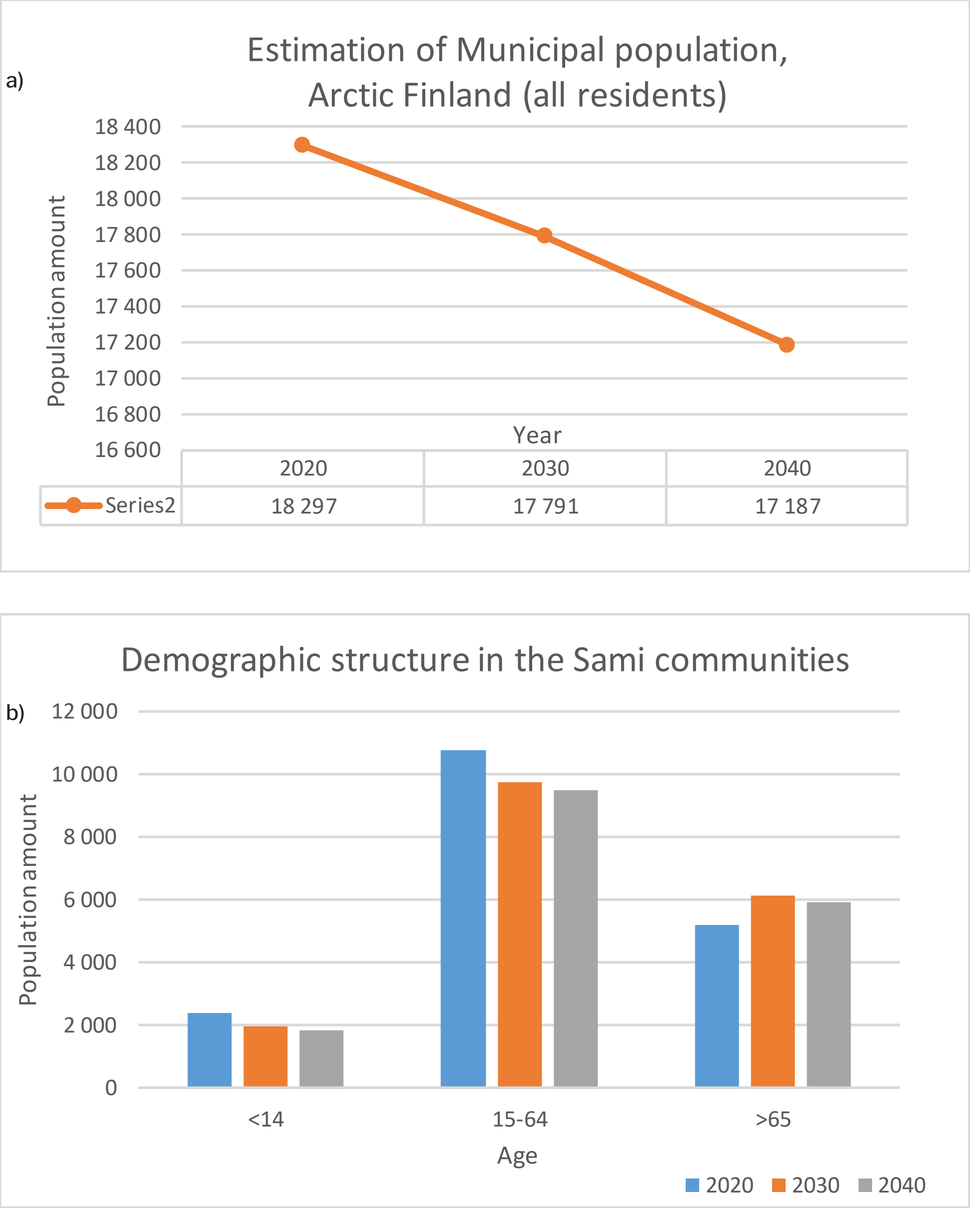

Figure 8. a). Estimate of Municipal population. b) Demography for Arctic Municipalities, Finland (Inari, Enontekiö, Utsjoki, Sodankylä).

Canada

According to the Köppen-Geiger climate classification system, there are 12 different types of climate in Canada[29]. The geographical distribution of these climates is presented in Figure 9. In the north, two climate types are mainly present: the subarctic and the tundra climates.

Subarctic climate is defined by a long, cold winter season with short days. There are 5 to 7 months where the average temperature is below freezing and temperatures can drop to below –50°C during that period.[30] Summer lasts between 1 to 3 months and average temperatures rarely exceed 16°C, except for interior regions where temperatures close to 25°C are possible. These annual temperature ranges are larger than those found in any other climate type. Humidity level is relatively low and there is little precipitation, which mostly takes the form of snow. Annual precipitation totals are usually below 380 mm. Away from the coasts, precipitation occurs mostly during summer, while in coastal areas the precipitation-heavy season is during the autumn months when the difference of temperature between the land and the seas is at its annual peak. Vegetation is generally of low diversity, since few species can survive the long winters. Trees are mostly conifers, with few broadleaved trees surviving the harsh conditions. Despite the low diversity of species, vegetation is quite widespread. With a surface area of 307 million hectares, Canada's boreal forest, the forested area within the subarctic climate, represents 75% of all forests and woodlands found in Canada.[31]

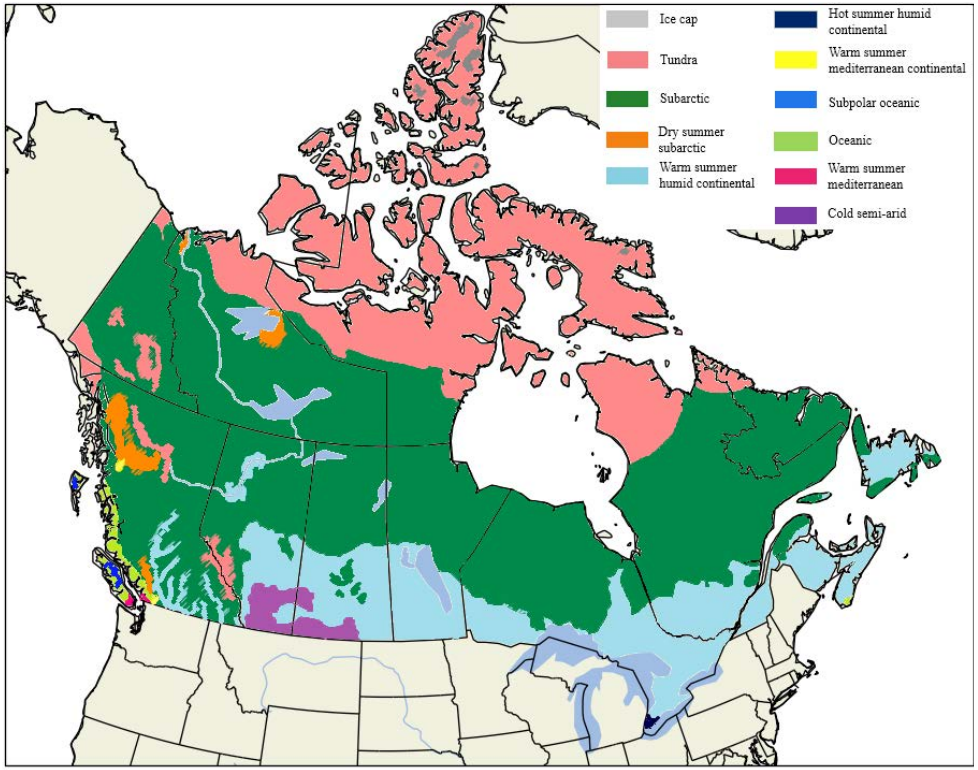

Figure 9. Climate types of Canada according to the Köppen-Geiger climate classification system.

The tundra climate is a transitional climate between the subarctic and ice cap climates. The climate is characterised by very cold and generally dry conditions. Temperatures rarely rise

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[29] Kottek et al. World Map of the Köppen-Geiger climate classification uptated. DOI: 10.1127/0941-2948/2006/0130

[30] The Physical Environment. Subarctic climate. https://www.earthonlinemedia.com/ebooks/tpe_3e/climate_systems/subarctic.html

[31] Natural Resources Canada. 8 facts about Canada's boreal forest. https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/sustainable-forest-management/boreal-forest/8-facts-about-canadas-boreal-forest/17394

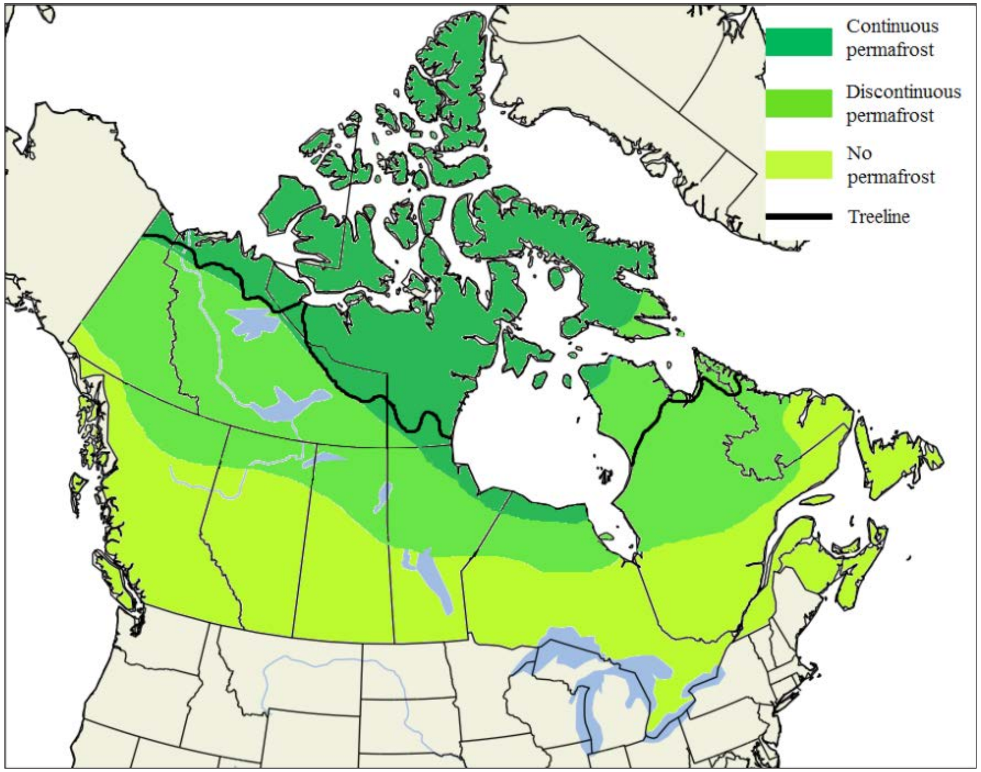

Figure 10. Distribution of permafrost in Canada and position of the treeline across the country.

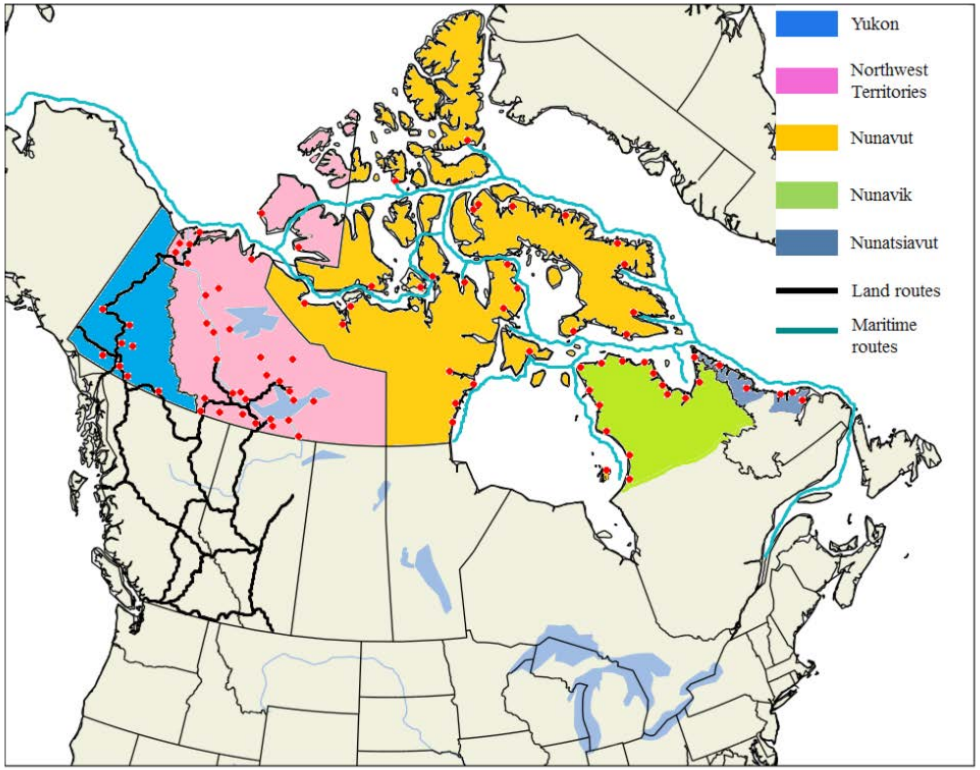

Figure 11. Road and marine transportation network in the north of Canada. Red dots represent the various communities located in the five regions and territories (only municipalities are shown for Yukon).

above 10°C during the summer[32]. Frost and snow are possible any month of the year. The very low temperature reduces the absolute humidity and consequently, precipitations are characteristically light (usually less than 250 mm per year). However, eastern and western reaches receive more precipitation (up to around 500 mm) due to the influence of the Atlantic and Pacific oceans. In the northern regions of the tundra climate, there are days in winter where the sun never rises above the horizon and days in summer where it never sets. For these reasons, the tundra climate is a region that is almost entirely devoid of trees (the treeline of Canada can be seen in Figure 10). Hardy flora survive in places by growing in rock depressions, where it is warmer and they are sheltered from the wind.

For both of these climate types, all moisture in the soil and subsoil freezes up to several meters' depth in winter. The summer season is too short and cold to thoroughly thaw the frozen soil, so permafrost prevails everywhere in the tundra climate and for a major part of the subarctic climate. Depending on the latitude and type of ground, permafrost can reach a thickness of many meters. The distribution of permafrost in Canada is shown in Figure 10. Continuous permafrost refers to a continuous sheet of frozen material that extends under all landscapes except large bodies of water. Discontinuous permafrost is broken up into separate areas. Permafrost is present in specific areas (e.g. in the shadow of a mountain or thick vegetation), but not everywhere since

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[32] The Physical Environment. Tundra climate. https://www.earthonlinemedia.com/ebooks/tpe_3e/climate_systems/tundra_1.html

the warmer climate is able to entirely thaw frozen soil for several weeks during summer.

Most Arctic communities in Canada are located in areas where permafrost is present to at least to some extent. Constructing infrastructures such as buildings on permafrost is challenging, because any heat release to the ground or change in the thermal balance can result in permafrost thawing, and thus create instabilities or even destruction of the infrastructure. Melting permafrost is also undesirable on a larger scale, as it would raise water levels and increase erosion in addition to affecting local ecosystems. Two common solutions to prevent buildings from thawing permafrost are to place the foundations of the building on wood or steel piles or to insert a thick (1–2 m) gravel pad that blocks the heat transfer between the building and the ground.

Figure 11 displays the road and marine infrastructure found in Canada's North. One of the more important differences between Canada's northern territories and the rest of the country is the absence of a road network for many isolated communities. There are 6,100 kilometres of road (59% of roads are unpaved) in Yukon, 5,400 km (78% are unpaved) in the Northwest Territories and 1,300 km (100% unpaved) in Nunavut.[33] Only two highways connect the north of Canada with the south and both are found in the west of the country. There is no road that connects Nunavut, Nunavik and Nunatsiavut with the rest of the country. Rail network is also minimal since the northern population is widely dispersed – only 0.2% of Canada's rail network is found in Yukon, the Northwest Territories and Nunavut.[34] The cold climate, uneven geography, great distances and small populations make the construction and maintenance of road and rail infrastructure difficult.

Since northern communities have little access to these two modes of transportation, a greater emphasis is placed on marine and air transport to bring in supplies and goods, and to satisfy the travel needs of individuals. The Northwest Passage, seen in blue in Figure 11, connects all presented communities of the north. Not all territories are able to take advantage of this passage. Approximately half of the population of the Northwest Territories lives in Yellowknife, which does not border the ocean. Whitehorse, the capital city of Yukon, accounts for 75% of the territory's population and has no regular marine service. To compare the two realities, Nunavut receives 153.2 thousand tonnes per year in shipment by boat versus 36.4 for the Northwest Territories, despite the latter having a larger population than the former.[35] In fact, 90% of the tonnage handled in Nunavut is related to importations via marine cargo. In the Northwest Territories, this proportion is 32%.

Air transportation is the common way of travel for individuals. In Iqaluit (Nunavut), Yellowknife (Northwest Territories) and Whitehorse (Yukon), the number of annual aviation passenger trips per capita respectively are 17.9, 15.1 and 6.6[36]. For the sake of comparison, Calgary is the city in the "south of Canada" with the biggest propensity to travel by airplane with 10.3 aviation passenger trips per capita. Calgary is an aviation hub with increased number of connecting flights, but cannot match the figures of Iqualuit and Yellowknife even with this upward effect. Because of the small population, the cost of flying is bigger in the North. The average household in Nunavut spends $1,803 per year on air travel. For all of Canada, this figure is $436.[37]

TOPOGRAPHIC AND DEMOGRAPHIC OVERVIEW

Northern Canada refers to the vast northernmost region of the country, represented politically by Canada's three territories (Yukon, Northwest Territories (NWT) and Nunavut), and by Nunavik and Nunatsiavut in the provinces of Quebec and Newfoundland and Labrador, respectively. These territories and regions are shown in Figure 12. Since 1925, Canada has claimed the portion of the Arctic between 60°W and 141°W longitude (the Atlantic and Pacific Coasts), extending all the way to the North Pole. Canada's North is typically divided into two distinct regions, referred to by biologists as biomes, comprising the Boreal Forest and the Tundra. The two biomes are separated by a transitional tree line many kilometers wide, which can also be viewed as the southern limit of the Arctic; the boundary between the Arctic and the Subarctic.[38]

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[33] Transport Canada. Transportation in Canada – 2018 Statistical Addendum. https://www.tc.gc.ca/eng/policy/transportation-canada-2018.html

[34] Statistics Canada. Transportation in the North. https://www150.statcan.gc.ca/n1/pub/16-002-x/2009001/article/10820-eng.htm

[35] Statistics Canada. Transportation in the North (Table 3 – Domestic shipping-tonnage handled, by territory, 2006). https://www150.statcan.gc.ca/n1/pub/16-002-x/2009001/tbl/transpo/tbl003-eng.htm

[36] Statistics Canada. Transportation in the North (Table 4 – Propensity to travel by airplane, 2006). https://www150.statcan.gc.ca/n1/pub/16-002-x/2009001/tbl/transpo/tbl004-eng.htm

[37] Statistic Canada. Transportation in the North (Table 6 – Household spending on transportation, Canada and the North, 2005). https://www150.statcan.gc.ca/n1/pub/16-002-x/2009001/tbl/transpo/tbl006-eng.htm

[38] The Canadian encyclopedia, John U. Bayly, Published Online February 7, 2006. https://www.thecanadianencyclopedia.ca/en/article/north

Canada’s tundra is known for its freezing temperatures, with strong winds and blizzards characteristic of the region’s long winters. The short summers are characterized by almost continuous daylight and its winters by long nights with only occasional daylight. Given the Arctic’s patchy vegetation and its low annual precipitation, it is often referred to as the “Polar desert”.[39] Canada’s Arctic region is sparsely populated. As of 2016, only about 129,352 people resided there; less than 1% of Canada’s total population.[40] A quantitative description of Canada’s North population is detailed in Chapter 2 of this report.

On the other hand, the Boreal zone (Taiga) takes up 55% of the Canadian land mass and is the country’s largest vegetation zone. It extends from Yukon and northern British Columbia in the west to Newfoundland and Labrador in the east. The region is also divided into three ecological subzones: the northern boreal woodland, the main boreal forest and the southern boreal forest.[41] Given Zero Arctic’s scope and objectives, this review of traditional indigenous architectures will only account for its most northern regions, the northern boreal woodland, closest to the three territories (Yukon, NWT & Nunavut), Nunavik in Quebec and Nunatsiavut in Newfoundland and Labrador. Even though the region is characterized by almost continuous permafrost, the climate in the northern boreal woodlands is not as harsh as in the Arctic regions and does allow for the development of widely spaced evergreens (coniferous trees that keep their foliage year-round).[42]

Indigenous groups make up more than half of the population in the three territories combined (85% in Nunavut, 25.1% in Yukon, 50.3% in the NWT), which are home to hundreds of different communities of varying sizes. In both Nunavik and Nunatsiavut, the share of indigenous people in the population is above 90%. Arctic peoples are one of the most culturally diverse groups.[43] Commonly, Indigenous peoples are classified using three major groups; the Inuit, First Nations & Métis. Although these broad categories will be used for classification purposes within the typology of vernacular architectures, it should be stressed that community members are more likely to define themselves as members of a specific nation, or communities within those nations, since the culture, languages and practices differ immensely amongst and within these categories.

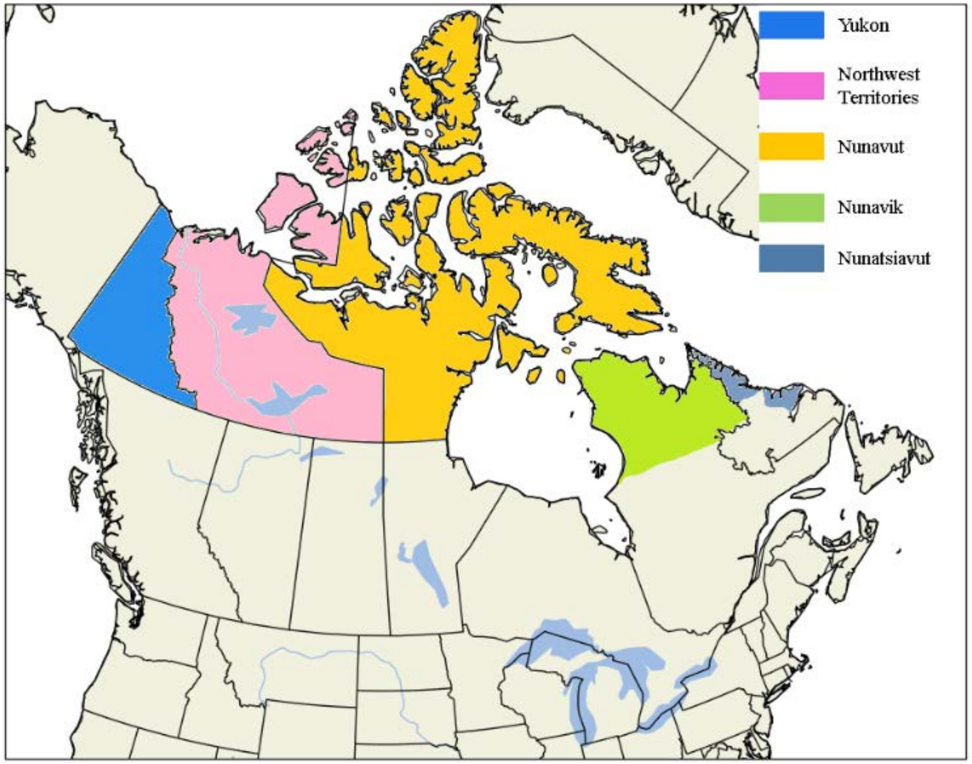

Figure 12. Map of Canada showing Yukon, Northwest Territories, Nunavut, Nunavik and Nunatsiavut.

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[39] The Canadian encyclopedia, J. Terasmae, Andrew Reeves, Published Online April 20, 2009. https://www.thecanadianencyclopedia.ca/en/article/tundra

[40] Government of Canada, Statistics Canada (8 February 2017). “Population and Dwelling Count Highlight Tables, 2016 Census”. www12.statcan.gc.ca.

[41] The Canadian encyclopedia. Article by George H. La Roi Published Online June 20, 2013 https://www.thecanadianencyclopedia.ca/en/article/boreal-forest

[42] The Canadian Encyclopedia, Article by John N. Owens. Published Online April 9, 2012 https://www.thecanadianencyclopedia.ca/en/article/coniferous-trees

[43] Government of Canada, Statistics Canada (15 January 2008). “Statistics Canada: 2006 Aboriginal Population Profile”. www12.statcan.gc.ca.

Japan

The island of Hokkaido is located at the north end of Japan. It has coastlines on the Sea of Japan, the Sea of Okhotsk, and the Pacific Ocean. A mountain range and a volcanic plateau run through the center of the island. Hokkaido has multiple plains such as the Ishikari Plain 3,800 km^2, Tokachi Plain 3,600 km^2, the Kushiro Plain is the largest wetland in Japan 2,510 km^2 and Sarobetsu Plain 200 km^2. Hokkaido is 83,423.84 km^2 which makes it second-largest island of Japan, and also the 21st largest in the world. The Tsugaru Strait separates Hokkaido from Honshu.[44]

Hokkaido has relatively cool summers and cold winters. The island falls in the humid continental climate zone with Köppen climate classification Dfb (hemiboreal) in most areas but Dfa (hot-summer humid continental) in southern areas. The average August temperature ranges from 17 to 22°C, while the average January temperature ranges from −12 to −4°C, in both cases depending on elevation and distance from the ocean. Temperatures on the western side of the island tend to be a little warmer than on the eastern. The highest temperature ever recorded is 39.5°C on 26 May 2019.[45]

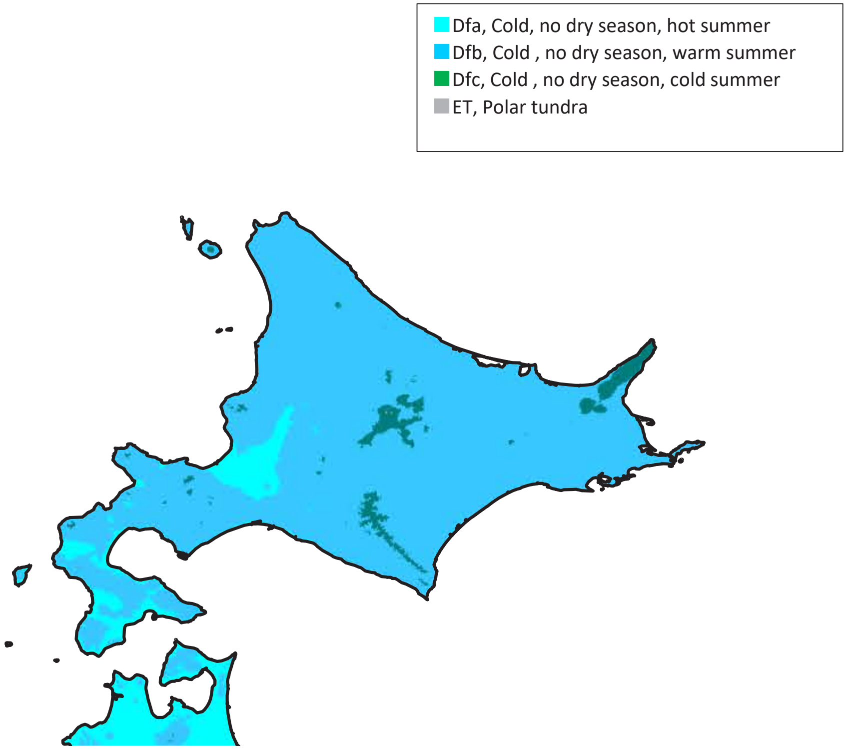

Figure 13. **Köppen-Geiger classification of Hokkaido.**
Present and future Köppen-Geiger climate classification maps at 1-km resolution, Nature Scientific Data: Beck, H.E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F

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[44] Nussbaum, Louis-Frédéric. (2005). “Hokkaido” in Japan Encyclopedia, p. 343, p. 343, at Google Books

[45] https://www.straitstimes.com/asia/east-asia/hokkaido-sizzling-in-temperatures-as-high-as-395-deg-c-as-unseasonal-heat-wave-grips

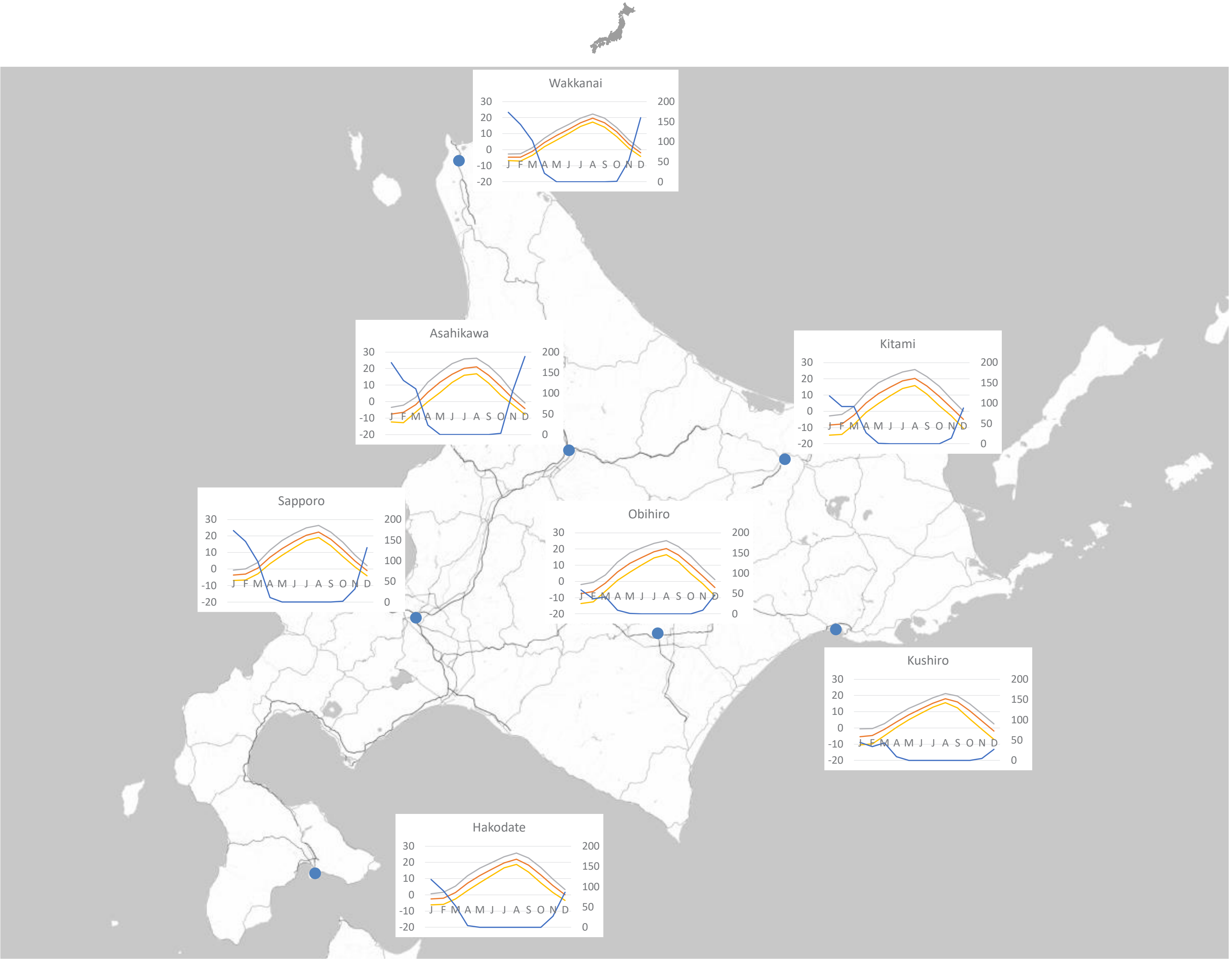

Figure 14. Temperature and snowfall around Hokkaido.
Maptiles by MIERUNE, under CC BY. Data by OpenStreetMap contributors, under ODbL.

The northern part of Hokkaido is in the taiga biome [46] with significant snowfall. Snowfall varies widely from as much as 11 meters on the mountains adjacent to the Sea of Japan down to around 1.8 meters on the Pacific coast. Total precipitation varies from 1,600 mm on the mountains of the Sea of Japan coast to around 800 mm, the lowest in Japan, on the Sea of Okhotsk coast and interior lowlands and up to around 1,100 mm on the Pacific side. Japanese mainland is normally affected by the rainy season caused by the monsoon. Hokkaido, however, is not affected by the rainy season. In winter, the generally high quality of powder snow and numerous mountains in Hokkaido make it a popular region for snow sports. Also, Hokkaido people celebrates its winter weather with several snow and ice events.

Figure 15 shows the predicted population change in Hokkaido and Ainus from 1920 to 2060.[47, 48,49] The most serious social problem in Hokkaido is rapid population decline. The peak of the population was approx. 5.7M around 2000. Hokkaido has already lost 500 000 individuals, 10% during the last 20 years. The population of Ainu is also rapidly decreasing, but the statistics before 1980 are not reliable.

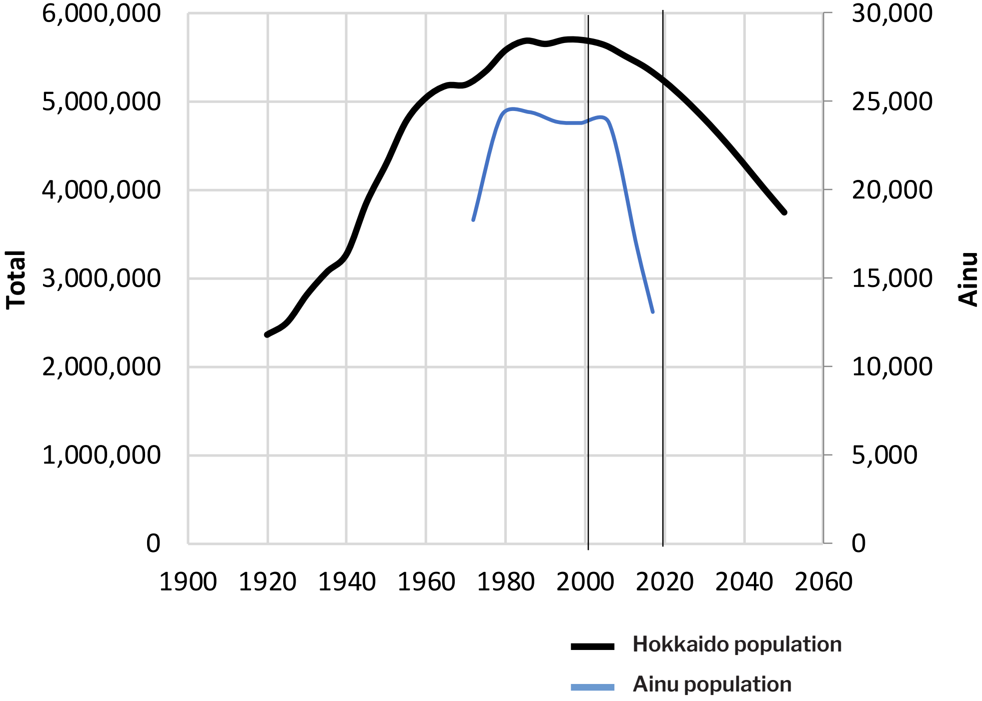

Figure 15. Population of Hokkaido and Ainu.

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[46] https://en.wikipedia.org/wiki/K%C3%B6ppen_climate_classification

[47] https://www.hkd.mlit.go.jp/ky/ki/renkei/ud49g70000000mki-att/en_all.pdf

[48] http://www.ipss.go.jp/index-e.asp

[49] https://www.ainu-assn.or.jp/english/life.html

3. VERNACULAR ARCHITECTURE

(in Finland, Canada and Japan)

Finland

The traditional Arctic construction in Finland consists of two different cultures that are 1) the Sámi, the indigenous people(s), and 2) the farming culture that has spread to the Arctic region from southern Finland from 18th century onwards. The differences of culture, traditions, livelihood and economy, and also traditional construction of the Sámi and the farming culture are significant. During the 20th century, modern construction techniques have substituted the tradition, and the few standing examples of vernacular Sámi architecture are mainly situated in museums.[50] Some traditional examples of the buildings of farming culture are still in use. Ethnological documentations, made from the late 19th century onwards, open a historical window to the vanished typologies of traditional construction and the use of dwellings.

An important source for the research has been the Sámi Museum Siida, the national museum of the Finnish Sámi population.

Figure 16. Map of Arctic Fennoscandia and the Sámi.

Figure 17. A log frame for a one-family house under construction. *Livady.*

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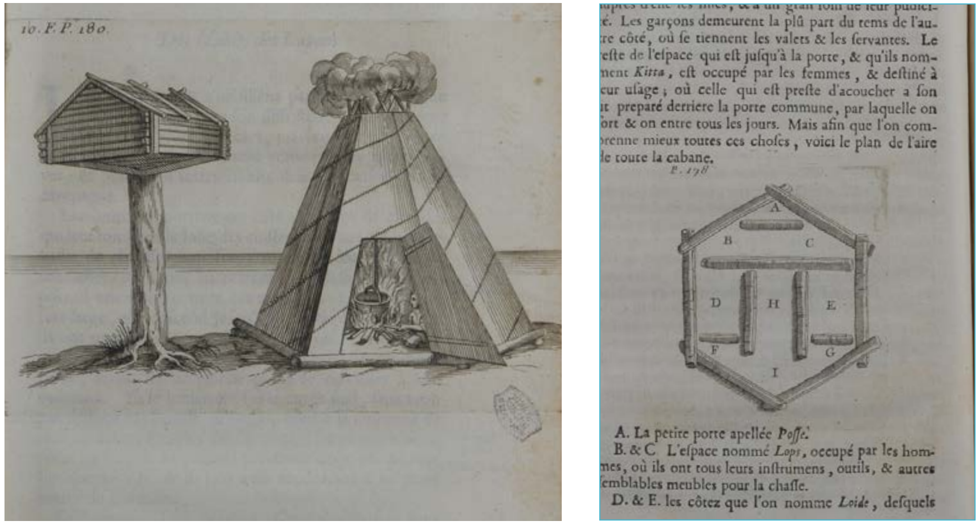
[50] Jomppanen, Arja, 2013. "Museoitu saamelainen kulttuuriympäristö: Inarin saamelaismuseo", teoksessa Magga, Päivi & Ojanlatva, Eija (toim.), *Ealli Biras — Elävä ympäristö. Saamelainen kulttuuriympäristöohjelma*. Saamelaismuseosäätiö, Inari, 112—113.

The Sámi

The Sámi are a Finno-Ugric people inhabiting northern parts of Scandinavia and North-Western Russia. The traditional livelihood and economy of the Sámi in arctic Finland is nomadic, mainly based on reindeer herding, together with hunting, fishing and gathering. The traditional architecture follows the needs of nomadic and seasonal livelihoods, consisting of various temporary and semi-permanent buildings and settlements. The materials used in traditional construction include wooden beams as supporting structures, logs (from 18th century onwards), and reindeer skins, boards, turf and moss as covering and insulating structures.[51]

As the last indigenous people in Europe, The Sámi (historically named also as “the Lapplanders”) culture and traditions aroused scholarly interest already in the 17th century. The earliest printed books depicting the traditional architecture of the Sámi date back to the 18th century. As the traditional buildings had a relatively short life cycle, no authentic standing examples exist. However, remarkable ethnological collections of interviews, photographs and drawings made from 1880s to 1950s make the traditional buildings and traditional knowledge accessible.

The historical terms used in this passage come from Northern Sámi.



é. Les garçons demeurent la plû part du tems de l'au-
tre côté, où ſe tiennent les valets & les ſervantes. Le
eſte de l'eſpace qui eſt juſqu'à la porte, & qu'ils nom-
nent *Kitta*, eſt occupé par les femmes, & deſtiné à
eur uſage; où celle qui eſt preſte d'acoucher a ſon
t preparé derriere la porte commune, par laquelle on
ort & on entre tous les jours. Mais afin que l'on com-
renne mieux toutes ces choſes, voici le plan de l'aire
le toute la cabane.

A. La petite porte apellée *Poſſe.*
B. & C L'eſpace nommé *Lops*, occupé par les hom-
mes, où ils ont tous leurs inſtrumens, outils, & autres
emblables meubles pour la chaſſe.
D. & E. les côtez que l'on nomme *Loide*, deſquels

Figure 18. Drawings of the facade and plan of a *Lávvu*, Histoire de la Laponie. *Jean Scheffer.*

Figure 19. Sámi village in Inari. Picture taken in the 1960s, photographer unknown. *Sámi Museum Siida.*

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[51] Magga, Päivi, 2013. “Saamelaisesta rakennusperinnöstä”, teoksessa Magga, Päivi & Ojanlatva, Eija (toim.), Ealli Biras — Elävä ympäristö. Saamelainen kulttuuriympäristöohjelma. Saamelaismuseosäätiö, Inari, 94—95.

The settlements

The historical Sámi settlements reflect the traditional nomadic livelihood. The traditional Sámi settlements differed substantially in different regions of Fennoscandia. The seasonal moves of Inari region and the divergent settlement patterns of the alpine regions of Northern Sweden reflect the various ways of adaptation to local geography and natural resources.[52] In general, the Sámi settlements highlight the complex interdependence of settlement patterns and scarce natural resources in the arctic region.

The seasonal move in the Inari region, characterized by separate summer and winter villages, reflects this central aspect of the Sámi culture in Arctic Finland. The summer villages were usually situated at the lakeshores, whereas the winter villages were set up in the sheltered forest areas, close to the reindeer pastureland. The distance between the summer and winter villages was seldom more than five kilometres. The seasonal move was preserved until the mid-20th century and the tradition vanished in the 1970s.[53]

The ethnological and archaeological material reveals that many of the village locations were permanent and used for centuries in some cases. Especially summer villages had permanent structures and also buildings when the Sámi adopted livestock-keeping, farming and log construction in the 18th and 19th centuries. The locations of winter villages were less permanent because of the need for firewood and pastureland resources.[54]

The settlement economy and seasonal moves demonstrate the adaptation to the scarcity of resources and the variation of summer and winter livelihood. They were also connected to the tradition on land ownership, based on kinship.[55]

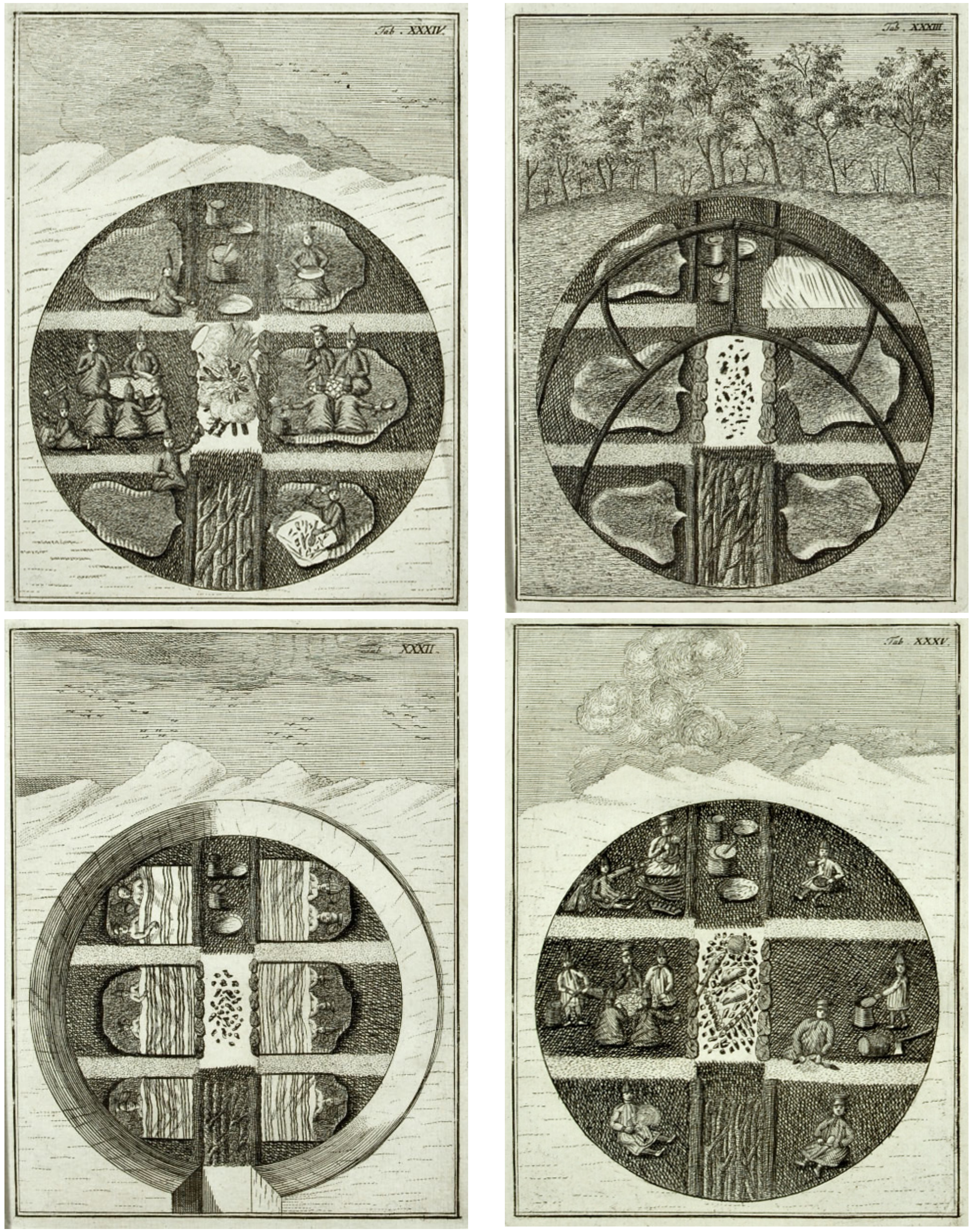

Figure 20. Sámi dwellings in 18th century engravingHistoire de la Laponie. *Jean Scheffer.*

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[52] Ojanlatva, Eija, 2013. “Variistâllâm - Inarinsaamelaisten vuotuismuutto”, teoksessa Magga, Päivi & Ojanlatva, Eija (toim.), Ealli Biras – Elävä ympäristö. Saamelainen kulttuuriympäristöohjelma. Saamelaismuseosäätiö, Inari, 74—75.

[53] Jeremoff, Irja, 2013. “Varriminen eli muutto talvipaikasta kesäpaikkkaan: Työtä ja vapautta”, Magga, Päivi & Ojanlatva, Eija (toim.), Ealli Biras – Elävä ympäristö. Saamelainen kulttuuriympäristöohjelma. Saamelaismuseosäätiö, Inari, 76–77.

[54] ibid.

[55] ibid.

Figure 21. *Lávvu* in Rommajärvi, Enontekiö. *Picture by Tyyne Hellen, Sámi Museum Siida.*

Figure 22. *Goahti*, historical photo. *Date and photographer unknown, Sámi Museum Siida.*

Lávvu

Lávvu represents the simplest heated dwelling in the vernacular architecture of Arctic Finland. It is a temporary form of dwelling that consists of a radial structure of primary and secondary battens and a fabric.[56] The structure can be partially open or almost totally closed. *Lávvu* is an example of a portable building that could be assembled of portable fabrics and battens gathered from nearby.

Goahti and hirsagoahti

A Goahti is the typical semi-permanent or portable dwelling of the Sámi. The supporting structure is composed of battens and the structure is covered with skins, fabrics or turf. *Goahtis* are both summer and winter dwellings and the structure allows various degrees of insulation, usually realized with turf. A *goahti*, as in the case of the *lávvu*, is divided into nine separate functional zones, the fireplace in the middle of the dwelling, described in detail in the figures.[57]

A *hirsagoahti* is an amalgamation of the traditional *goahti* and log construction adopted by Sámi in the 18th and 19th centuries. In a *hirsagoahti*, the foundation is laid of logs in rectangular, hexagonal or octagonal form up to one meter. Upon the log foundation the structure follows the principles of *goahtis*, described above.[58]

The life cycle of *goahtis* was at maximum a few decades. *Goahtis* and settlements were usually abandoned due to firewood resources that forced to transfer to a new settlement. When log construction was adopted, the log foundations were usually recycled to new buildings.

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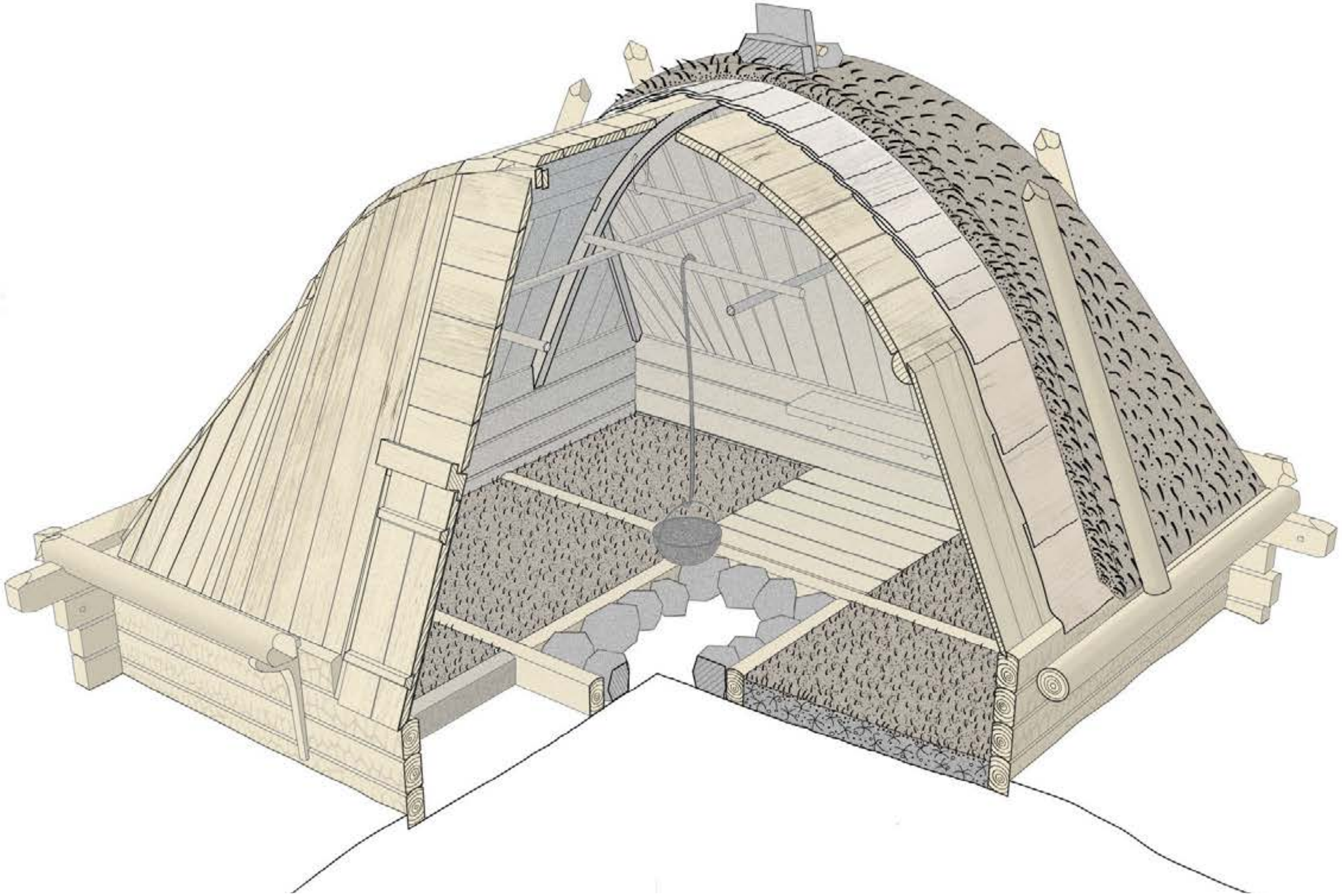
[56] Itkonen, T. I. 1948. Suomen lappalaiset vuoteen 1945, I osa, 175–178.

[57] Itkonen 1948, 178 — 193.

[58] Huttunen, Marko, 2013 “Salvoskota, hirsitupa ja hirsitalo – Inarinsaamelaisten vanhat hirsiasumukset”, Magga, Päivi & Ojanlatva, Eija (toim.), Ealli Biras — Elävä ympäristö. Saamelainen kulttuuriympäristöohjelma. Saamelaismuseosäätiö, Inari, 98—109; Itkonen 1948, 193—197.

Figure 23. *Goahti*, 3D section. *Livady.*



Sámi log house

The Sámi adopted the log house construction simultaneously with the initiation of the constructions of *hirsagoahtis* in the late 18th century. In a log house, the heating was organized with a chimneyless stove, situated in the corner of the house. As in the *goahtis* and the *lávvu*, the space was divided into functionally separate zones, but with a wooden flooring as a new feature.[59]

Figure 24. Sámi log house. *Livady.*

Storage shelters and houses

Besides the dwellings, the livelihood required a number a storage houses. The most simple constructions were shelters, supported by four beams and covered with fabrics and turf. A *njalla* is a historically important type of storage house often depicted in the illustrations of early books about the Sámi. A *njalla* consists of a small rectangular storage room for game, mounted on a pole. After the adoption of animal husbandry and farming, the number and types of outbuildings was multiplied, and the Sámi adopted the building types of the southern farming culture.

Figure 25. Sámi log house, historical photograph.

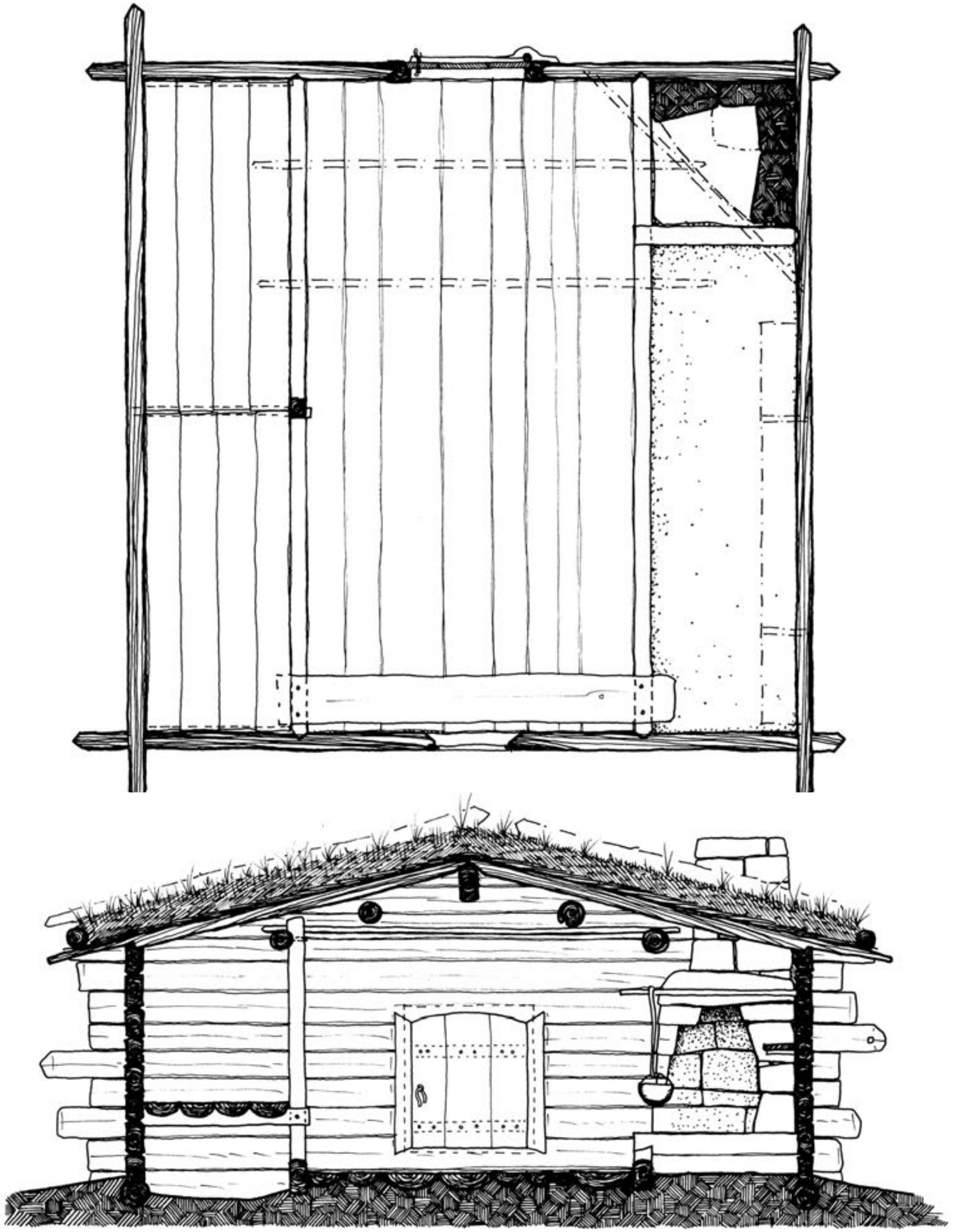


Figure 26. Sámi log house, drawing of section and plan. *Livady.*

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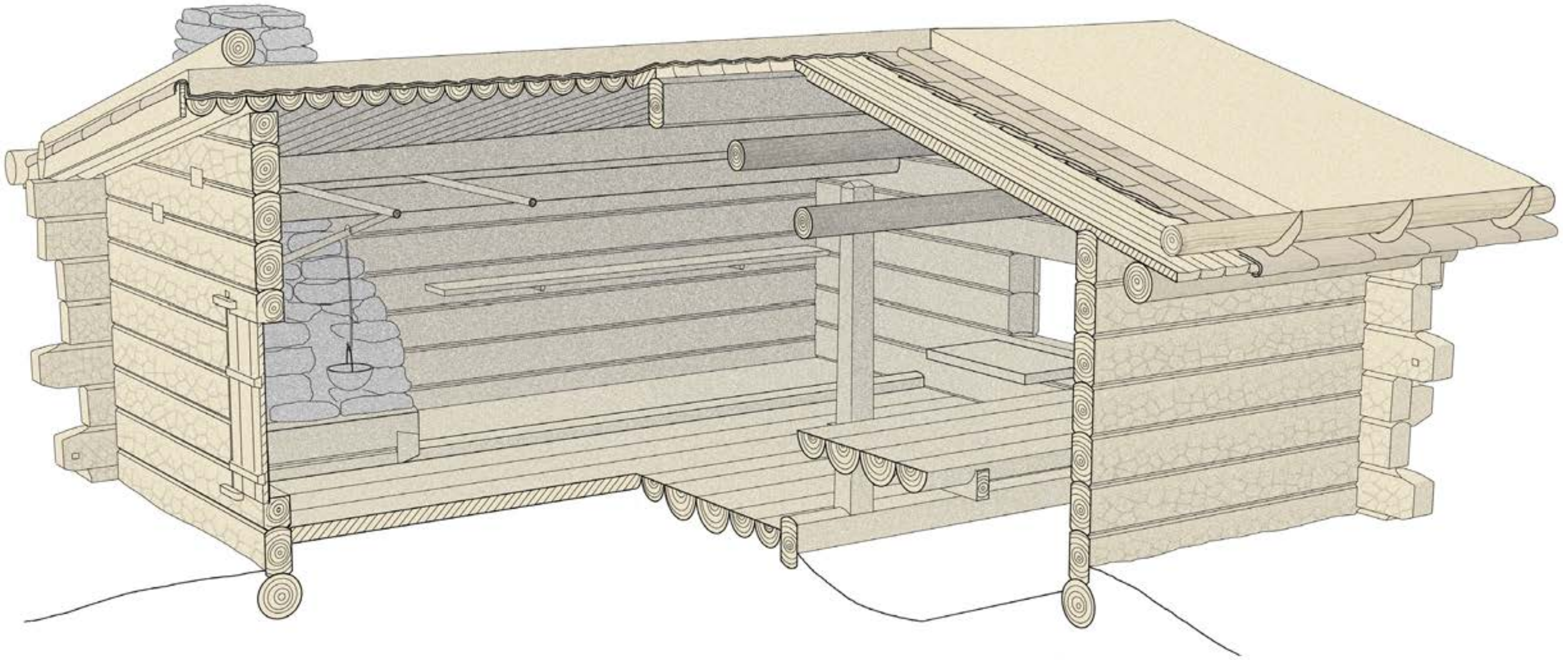
[59] Huttunen 2013, 101; Itkonen 1948, 205—2015.

Figure 27. Sámi log house, 3D section. *Livady.*



The building types of farming culture in Arctic Finland

Smoke house (chimneyless log house)

The smoke house is the earliest dwelling type of the farming culture that spread to the Arctic Finland from 16th century onwards. Smoke houses represent the traditional log construction, typical in Scandinavia and Russia already in the end of the first millennia. Smoke houses contained initially only one room, but buildings with two or even several rooms exist from 16th century onwards. The name, smoke house, comes from the heating system where the smoke circulates inside and heats the massive structure. The smoke is then conducted outside through vents. Some smoke houses with modernized heating still stand, but the tradition of heating without chimneys is conserved only in smoke saunas.

Figure 28. Smoke house and log house with chimney in Murtovaara. *Livady.*

Figure 29. Smoke house in Murtovaara. *Livady.*

Log house (with chimney)

Log houses are based on the same tradition of construction as smoke houses. The most important difference is the chimney and the structural and indoor characteristics that derive from the introduction of the new heating system. Log houses substituted smoke houses in Arctic Finland from 17th century onwards, and largely during the 19th century. The introduction of the chimney resulted in the construction of ceilings to economize heating. Log houses were the only type of dwellings in the farming culture of Arctic Finland up to the second world war, and there are still a number of standing examples in use.

Storage shelters and houses

The storage houses and shelters needed in the farming culture were completely different when compared to the nomadic Sámi. Most common outbuildings were granaries and buildings needed for animal husbandry. In farming culture, all the buildings were located close to each other, and the livelihood did not demand seasonal moves.

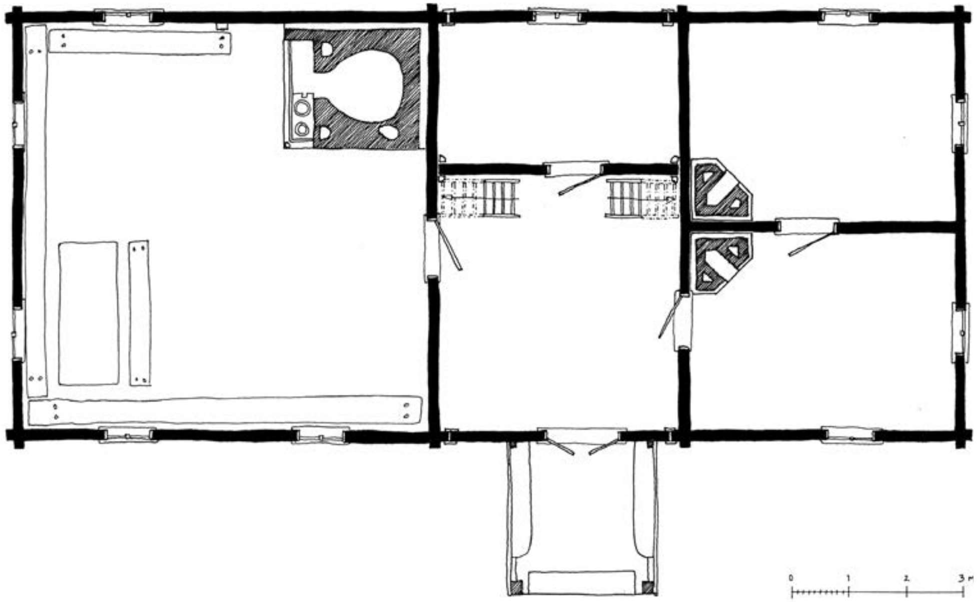


Figure 30. Plan of chimney house. *Livady.*

Figure 31. Log house. *Livady.*

Figure 32. Transfer marks in the logs of a log house. *Livady.*

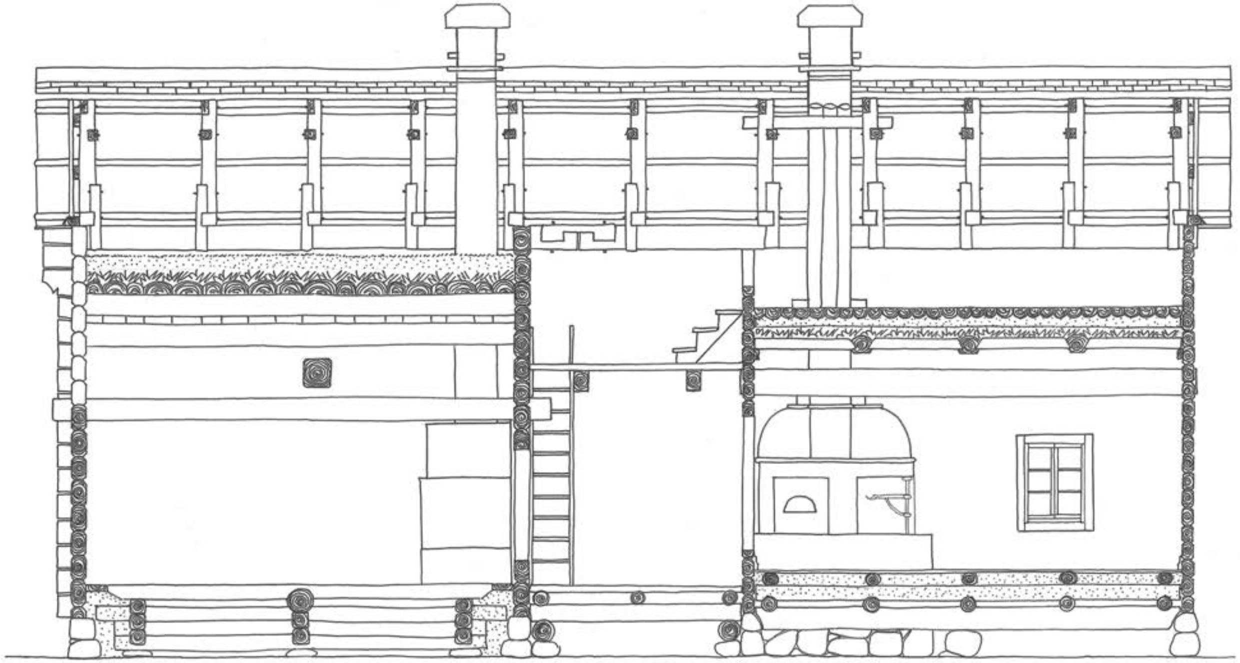
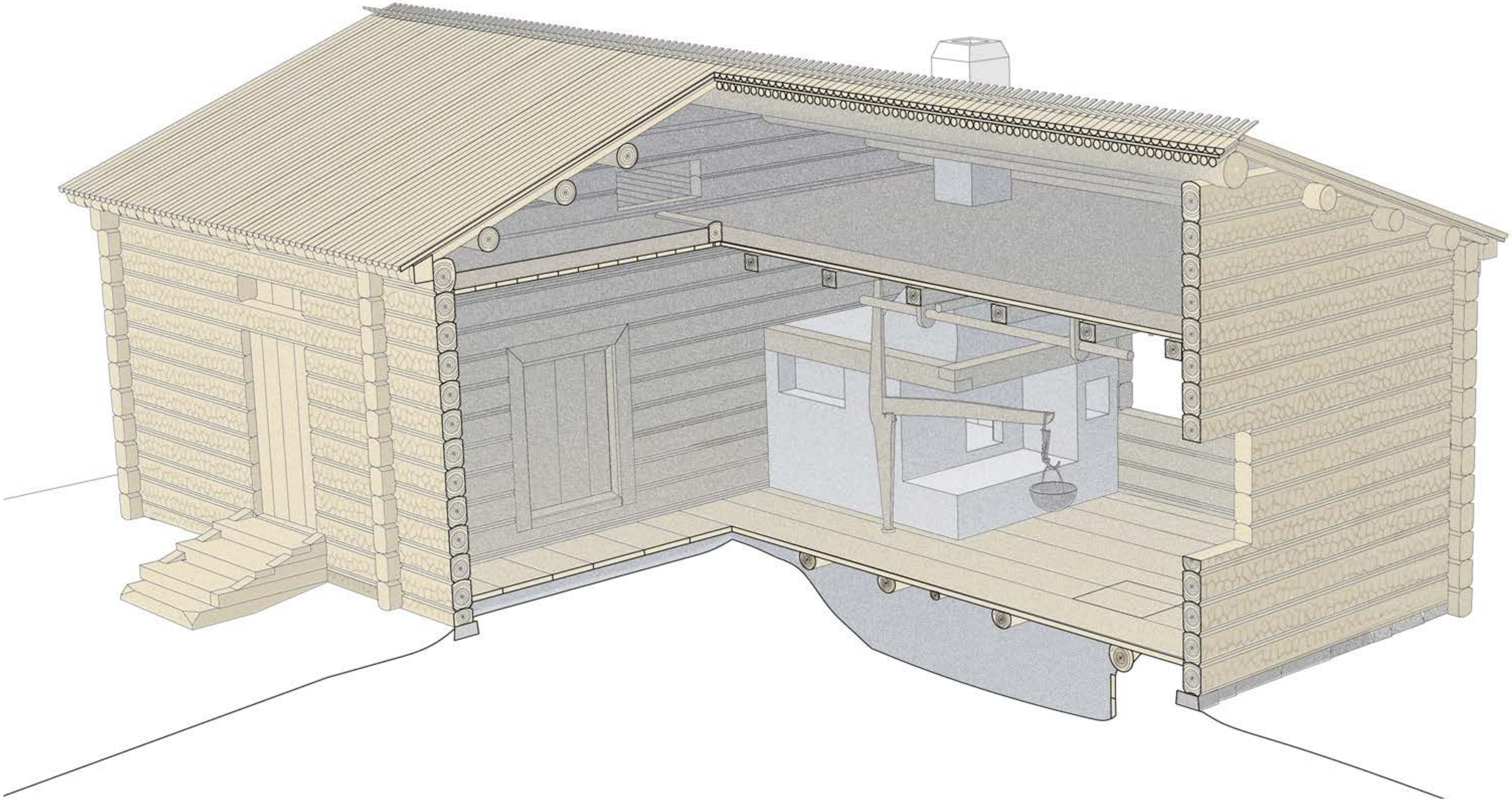


Figure 33. Section drawing of a log house. *Livady.*

Figure 34. Log House with chimney, 3D section. *Livady.*



Vernacular architecture of Inuit and their Thule ancestors

Up until the 1950s, Inuit were primarily a semi-nomadic people who maintained patterns of regional, seasonal migration across Inuit Nunangat (i.e. Nunavut, Nunatsiavut, Nunavik and Inuvialuit) that were based on the availability of natural resources and supported their traditional subsistence practices. Inuit relied upon hunting and fishing for their main source of food and followed the seasonal migration patterns of animals. During the winter months, extended family groups lived in coastal areas in winter camps of up to 100 inhabitants where they could socialize and hunt seals. In spring and summer, Inuit moved inland in smaller groups of a dozen people or less in order to fish and hunt large game such as caribou.[60] Inuit constructed dwellings made from the scarce natural resources available to them that reflected their seasonal nomadic lifestyle; from *igloos* in winter, to *tupiq* in summer, and *qarmaq* for in-between seasons. "This architecture involved small houses prized for their portability and construction ease, such as skin tents, and houses made from

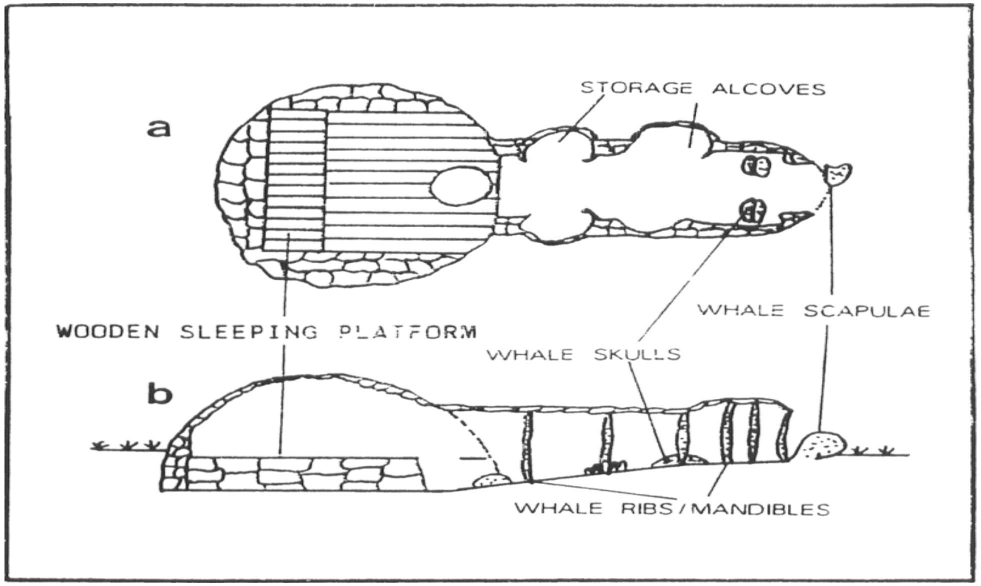


Figure 35. Cross-section of northwest Thule whale bone and sod dwelling.
Savelle 1987: 57 after Spencer 1959: 49.

Figure 36. Community of igloos in 1865.
Arctic Researches and Life Among the Esquimaux (1865) by Charles Francis Hall (public domain)

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[60] http://firstpeoplesofcanada.com/fp_groups/fp_inuit4.html

sod, snow and wood."[61] The following section presents a short overview of different Inuit vernacular dwellings

Thule Winter House

As explained by Dawson,

> "many archaeologists describe "true" semi subterranean Thule winter houses as constructed from cut sod, stone, and whale bone, and possessing cold-trap entrance tunnels, rear sleeping platforms, a kitchen area (either spatially discrete or integrated into the main living area), and various storage areas (shelves, boxes) for stowing food, tools, and other household items".[62]

Typically, a Thule winter house's footprint was an oval (diameters between 3 and 9 m), see Figure 35. The floor was as much as 1 m into the ground. The structure was typically made from whalebones.[63] Houses were often clustered in groups, suggesting communities of 20 to 125 people,[64] but there is evidence that all the houses of these clusters were not necessarily occupied at the same time.[65]

Figure 37. Inuit building an igloo in 1924.

Frank E. Kleinschmidt - Library of Congress Prints and Photographs Division, Washington, DC 20540, Photograph. shows Inuit constructing an igloo with blocks of snow as children and dogs stand by (25 November 1924).

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[61] Bonesteel, S. (2006). Canada's Relationship with Inuit: A History of Policy and Program Development, June 2006, https://www.aadnc-aandc.gc.ca/DAM/DAM-INTER-HQ/STAGING/texte-text/inuit-book_1100100016901_eng.pdf, pg. 59.

[62] P.C. Dawson, Interpreting Variability in Thule Inuit Architecture: A Case Study from the Canadian High Arctic, American Antiquity, Vol. 66, No. 3 (Jul., 2001), pp. 453–470

[63] Canadian encyclopedia. Architectural History of Indigenous Peoples in Canada. Article by Edward Mills, Published Online September 30, 2007 https://www.thecanadianencyclopedia.ca/en/article/architectural-history-early-first-nations

[64] https://www.glenbow.org/thule/?lang=en&p=outside&t=enhanced&s=3–1&mi=1

[65] R.W. Park, Thule Winter Site Demography in the High Arctic, American Antiquity, Vol. 62, No. 2 (Apr., 1997), pp. 273-284.

Igloo (Inuit Snowhouse)

Snow houses or igloos are probably the most iconic type of Inuit dwellings. They have been one of the predominant winter dwelling forms in the North (Figure 36). Its history might date back to the Dorset people, who preceded the Thule in the area. Archeologists have discovered snow knives indicating that Dorset might have built igloos as remotely as 1000 AD.

Snow houses are a good example of passive vernacular architecture, taking advantage of the environment in which it is built. In addition to being abundant, snow is a highly insulating material, with a thermal conductivity that can be as low as that of modern insulations. Only body heat and oil lamps heated the indoor environment, as fuels such as wood were not available in many locations.

To erect an igloo, a row of snow bricks was aligned in circle and then trimmed in order to create an upward spiral,[66] as shown in Figure 38. More snow bricks were then added, gradually increasing the inclination of the edges between successive rows until the desired dome shape was achieved. Interstices were packed with snow. Typically, the diameter of an igloo housing a family would be around 3.5–4.5 m, and its height around 3–3.5 m. Smaller igloos were also used as temporary shelters.[67]

The dome shape had several advantages from a bioclimatic perspective.[68] A dome is a shape that has a small exposed surface to volume ratio. This limits heat losses compared to other shapes, such as a box or a cube shape. Another advantage of this shape is that it experiences essentially compression stresses and can thus be made of materials with a weak tensile strength, such as snow. The shape of the dome provides a low wind resistance or drag, and helps to reduce turbulence in the environment around the igloo.

The entrance of the igloo can have a cold-trap to prevent the infiltration of cold air. Essentially, it consists of a tunnel passing below the wall of the igloo and then going up inside. The principle behind the cold-trap is that a stable thermal stratification will be created, in which cold and denser air will occupy the tunnel, and warmer and lighter air the inside of the igloo. The interior of the igloo could slightly melt due to body heat or oil burning, and later refreeze; creating a thin layer of ice that strengthens the igloo and increases its air tightness.

A small hole at the top of the igloo served for ventilation, in order to provide an acceptable indoor air quality for the people without increasing too much the heat losses.

Depending on the communities, several variations existed in igloo designs and layouts:

"Details of design differed from one region to another. Some used skin linings, while others did not. Entranceways might be flat-topped (as among the Inuinnait (Copper Inuit)), rather than vaulted or domed. Igloos were sometimes arranged in clusters, with a number of living chambers sharing a common entry tunnel or a communal facility, such as a feasting room or a dance house. Some clusters, as among the Iglulingmuit of Hudson Bay, might have as many as 10 domed units, each with a discrete function (e.g. living unit, dog kennel, storage)".[69]

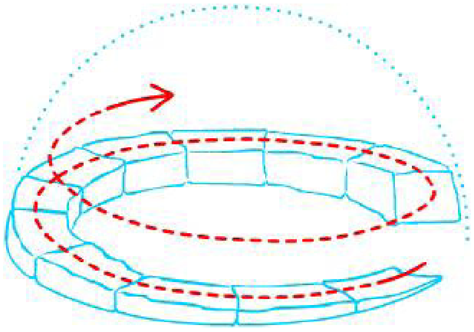

Figure 38. Illustration of the upward spiral construction of an igloo.
Image from public domain.

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[66] Did you know? How to Build an Igloo, Canadian Polar Commission, Published Online 2016-06-10 (link).

[67] Canadian encyclopedia. Architectural History of Indigenous Peoples in Canada. Article by Edward Mills, Published Online September 30, 2007 https://www.thecanadianencyclopedia.ca/en/article/architectural-history-early-first-nations

[68] U. Degringny, La construction passive, Chapitre 2 - Conserver la chaleur : l'exemple Inuit, Fiabitat, 26 septembre 2008 (link).

[69] Canadian encyclopedia. Architectural History of Indigenous Peoples in Canada. Article by Edward Mills, Published Online September 30, 2007 https://www.thecanadianencyclopedia.ca/en/article/architectural-history-early-first-nations

Igluryuaq

Until the beginning of the 20th century, the Inuvialuit of the western Canadian Arctic built their winter dwellings from driftwood, which they covered with blocks of sod and earth for insulation.[70] This type of house is called *igluryuaq* Figure 39. In winter, an *igluryuaq* would look like a large snow dome due to snow accumulation.[71]

One would enter an *igluryuaq* through a porch made of snow blocks, followed by a long tunnel built below the level of the dwelling's floor. Similarly to the entry of an igloo, the tunnel trapped the cold and denser air and prevented it from entering the built environment, where air is lighter and warmer.

An *igluryuaq* often had three rooms opening up on a central area. Since the heat generated by people and oil burning tends to go up, raised platforms were installed where people could sit, sleep, work, etc., in the warmest part of the dwelling. Windows in the roof could provide lighting in addition to oil burning lamps. Venting was also performed through the roof.[72] A reconstitution of how an *igluryuaq* was built is available online.[73]

Figure 39. Entrance of an *igluryaq* (1924) .

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[70] Idem.

[71] https://web.archive.org/web/20131021062131/http://www.inuvialuitsodhouse.ca/dwellings/cold-season/

[72] R.M. Levy, P.C. Dawson, C. Arnold, Reconstructing traditional Inuit house forms using three-dimensional interactive computer modelling, Virtual Realities, Vol. 19., No. 1., 2004.

[73] https://www.youtube.com/watch?v=lBdYkPMLA5M

Figure 40. Above: Example of *Qarmaq* in Qausuittuq (Resolute Bay), Nunavut and in Akulivik (Nunavik) Below: Qarmaq located near the Northern Village of Akulivik, Nunavik, Maxime Rochette, Living in Northern Quebec. *Copyright pending: https://www.newberyphotoarchives.ca/in/photos/5-qarmaq.*

Qarmaq (Transitional Dwelling)

Qarmaq are inter-seasonal houses used by the Inuit, when tents were no longer adequate in the fall and when ice and snow began to melt in the spring.[74] Different forms of *qarmaq* were possible depending on the regions and the available materials. They are often described as a hybrid between a tent and an igloo.

As shown in Figure 39, a *qarmaq* essentially has a base of snow blocks or stones, a whale bone framework and an animal skin cover.[75] According to the Avataq Cultural Institute (the Inuit cultural organization of Nunavik), a *qarmaq* is “a semi-subterranean house used as shelter in spring and fall”.[76] Walls are made of peat sods that were cut into blocks.[77] Labrèche mentions “fall *qarmaq*”, which is a tent covered with skin and moss, with a snow packed low wall, and “spring *qarmaq*”, built from the base of an igloo when it starts to melt.[78]

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[74] https://web.archive.org/web/20131021062131/http://www.inuvialuitsodhouse.ca/dwellings/cold-season/

[75] Sheppard, Lola & White, Mason. Many Norths: Spatial Practice in a Polar Territory. Actar. 2017. P.146

[76] http://www.avataq.qc.ca/en/Les-Nunavimmiuts/Le-territoire/Lexique

[77] http://kingulliit.avataq.qc.ca/qarmaq-eng

[78] Y. Labrèche (2003), Habitations, camps et territoires des Inuit de la région de Kangiqsujuaq-Salluit, Nunavik, Études/Inuit/Studies, 27 (1–2), 155–190.

Tupiq (tent)

Summer was an active period of the year for hunting and fishing, requiring communities to move frequently to follow their preys. Several types of tents could serve as dwellings for Inuit during that season.[79] Tents were portable and had the advantage of being easy to assemble (or dissemble).

The *tupiq* is a simple type of tent, made by assembling poles to form structure and covering it with skins of seal, caribou or other animals. *Tupiq* came in many variants, including the conical shape and the design with a ridgepole. For example, the Inuit along the Labrador coast, as well as some central groups "built tents with a conical rear portion and a triangular entrance area, with a horizontal ridgepole between the two", [80] similar to what can be seen in Figure 41.

Figure 41. Inuit family in front of a tent (year unknown).
http://firstpeoplesofcanada.com/fp_groups/fp_inuit6.html

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[79] https://web.archive.org/web/20131021052212/http://www.inuvialuitsodhouse.ca/dwellings/warm-season/

[80] Canadian encyclopedia. Architectural History of Indigenous Peoples in Canada. Article by Edward Mills, Published Online September 30, 2007 https://www.thecanadianencyclopedia.ca/en/article/architectural-history-early-first-nations

Vernacular architecture of First Nations of the North

The difficulty with documenting the architecture of First Nations in Canada lies within several realities: cultural diversity, geographical isolation, and varying traditions. Moreover, since our interest for this project is primarily related to northern populations, discerning from the limited available resources has proved challenging.

The Subarctic regions extend from east to west of Canada, covering over 5 million square kilometers. First Nations occupying this territory are many and include speakers of Algonquian languages such as Cree, Naskapi, Innu and Ojibwa in the east, and of Athapascan languages in the west, such as Dene, Han, Gwich'in and Tutchone. Some non-exhaustive examples of traditional housing of these nomadic or semi-nomadic people are presented below.

A *wigwam* is defined as "a rounded structure made from a frame of poles covered with materials such as grass, cloth, or animal skins".[81] Different First Nation communities used this type of shelter, adapting its size and shape to their needs and to available materials, including the Cree of the North among others.[82] According to the Canadian Encyclopedia, "the difference was that they typically built circular, elongated and domed *wigwams,* usually as winter dwellings, and clustered in settlements. Cut saplings were set upright into the ground at intervals of about 60 cm. Opposite poles were bent towards the centre and their ends tied together with strips of wood. Horizontal members were added to strengthen the stressed frame. The lower portion might be sheathed with a row of mats woven from cattails, the upper part with sheets of bark".[83]

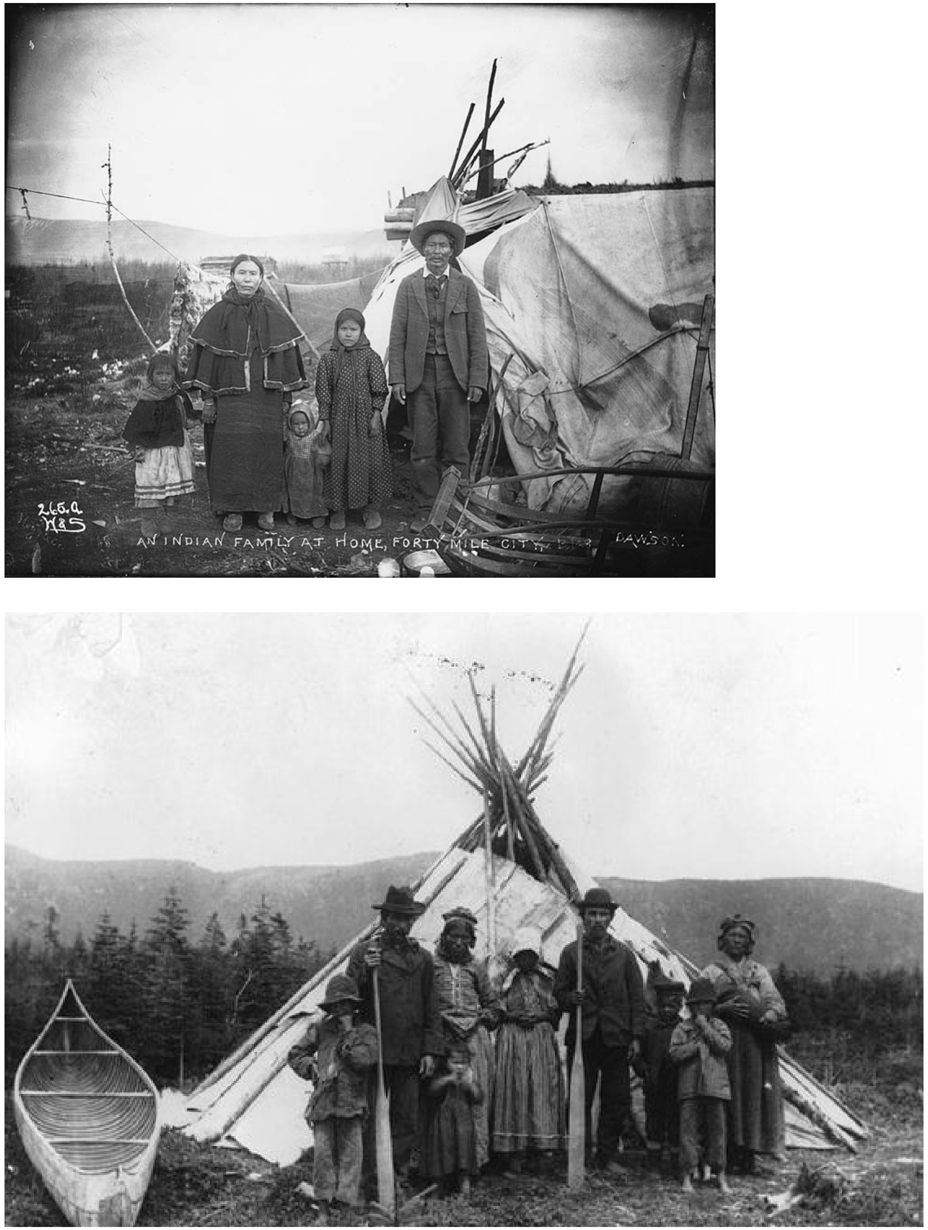

Figure 42. Innu group at Mingan (Quebec) in 1920 and Gwich'in group in 1889, both in front of their houses.

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[81] Cambridge Dictionary, 2020.

[82] Canadian encyclopedia. Architectural History of Indigenous Peoples in Canada. Article by Edward Mills, Published Online September 30, 2007
https://www.thecanadianencyclopedia.ca/en/article/architectural-history-early-first-nations

[83] Idem.

Innu families lived in conical tents with a diameter of 4 to 6 meters as shown in Figure 42. Caribou skins or bark would serve to cover the poles of the structure.[84] First Nations of the Mackenzie and Yukon Rive Basins used similar tents.[85]

These homes were well suited for nomadic people, being portable and easy to build from local materials. Other interesting examples of Innu tents are shown in Figure 43.

Figure 43. Examples of traditional Innu tents, Uashat Mak Mani-Utenam (Québec).
Antonin Cartier Boulanger, Université Laval (Habiter le nord québécois).

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[84] https://editioninnu.wordpress.com/2013/02/18/lhabitat-traditionnel/
[85] https://www.rcaanc-cirnac.gc.ca/eng/1307460755710/1536862806124

An example of contemporary vernacular: Nunavik's cabins

Indigenous know-how and ingenuity continue to come out in modern northern architecture and land-use. Cabins that complement Inuit current housing in Nunavik and elsewhere in the North are a good example of this contemporary vernacular that combines material re-use, low-energy, symbiosis with the site and local knowledge. Studies of current Inuit cabins were part of a project called "*Habiter le Nord Québécois* / Living in Northern Quebec",[86] a recent major collaborative research partnership that focuses on the culturally adequate and sustainable living environments of the Nitassinan Innus and Nunavik Inuit.

Figure 44. An Inuit camp in Salluit Fjord, Nunavik. *P.-O. Desmeule.*

In Nunavik, the transition from traditional nomadic settlements to the establishment of Northern Villages was marked by a succession of state-funded housing programs,[87] the emergence of community services provided by a system of governance involving several organizations, and an accelerating urbanization process.[88] The majority of Nunavimiut (inhabitants of Nunavik) live along the coasts of the Hudson and Ungava Bays, in 14 villages varying in size from about 200 to 2,750 inhabitants.[89] Outside the villages, family camps provide access to the land (or *Nuna*) for traditional activities centered on hunting, fishing and gathering. While the villages represent service points and a link to the rest of the province, the land remains a strong symbolic anchor and a place for cultural expression.[90] Even today, hunting and fishing products are an important part of Inuit's food supply.

The form of Nunavik villages follows suburban models from the South, with repetitive blocks of houses interspersed with community buildings and services. Most buildings are implemented on increasingly unstable permafrost, which imposes a widely used, yet costly, system of gravel pad foundations. Instead of underground infrastructure, a door-to-door truck service supplies drinking water and retrieves sewage at all time.[91] This planning strategy limits the availability of safe zones for construction and dictates a reflection on alternative ways of building and planning, which also take into account climate change effects.[92] In fact, the current housing production and development patterns in Nunavik impose strongly felt constraints on local autonomy and capacities, as well as the control the Inuit can exercise over their living environment.[93]

For the Nunavimmiut, the practice

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[86] www.habiterlenordquebecois.org

[87] Duhaime, G. (1985) De l'igloo au H.L.M. : les Inuit sédentaires et l'Etat-providence. Québec, Centre d'études nordiques.

[88] Desbiens, C (2017) Un nouveau sens du lieu ? « L'effet urbain » dans les communautés du Nunavik. Recherches amérindiennes au Québec, 47(1), 151–154.

[89] Statistique Canada (2016) Profil du recensement de 2016. https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=F&TABID=1. Consulté le 21 février 2020.

[90] Landry, J (2018) Sédentarisation au Nunavik: identités, territorialités et territoires inuit contemporains. Essai en design urbain, École d'architecture de l'Université Laval, Québec.

[91] Vachon, G, E Rivard, M Avarello and L St-Jean (2017) Imaginer l'aménagement soutenable des villages inuits du Nunavik : le design pour réfléchir aux possibles. Recherches amérindiennes au Québec, 47 (1) :137–150.

[92] Allard, M, M Lemay, M Barrett, T Sheldon and R Brown (2012) From Science to policy in Nunavik and Nunatsiavut: Synthesis and Recommendations. In Allard, M and M Lemay (chief editors) Nunavik and Nunatsiavut: From science to policy. An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization, 72 p.

[93] Hervé, C and P Laneuville (2017) La quête d'autonomie résidentielle des femmes inuites du Nunavik : une perspective relationnelle. Recherches amérindiennes au Québec, 47(1) : 49–58.

Figure 45. Cabins on a rocky outcrop near Salluit, Nunavik. *P.-O. Desmeule.*

of the land has always been crucial to the survival of communities. In order to extend in time and space their traditional hunting, fishing and gathering activities, many of them are engaged in the self-construction of camps and cabins along their seasonal routes. As part of the evolution and adaptation of a close relationship with the territory, these cabins are humble, even frugal constructions, erected without normative constraints. Made from objects and materials mostly recycled or "hacked", they highlight the principles of Inuit *Qaujimajajatuqangit* (what the Inuit have always known). On a cultural level, they also serve as spaces for socialization, for the intergenerational transmission of knowledge, and for hosting "healing circles". In this sense, tundra camps are certainly one of the key pillars of Inuit identity and well-being.[94]

Contemporary vernacular architecture implies that the local know-how, combined with the adaptation of construction practices and the use of local materials, allows for a sustained and fruitful co-dependence of culture, economy and local ecosystems.[95] Nunavik's camps and cabins have a small ecological footprint which promotes passive strategies and the use of healthy, natural materials such as snow, recycled wood, stone, earth, peat, as well as sealskin, caribou guts, goose down and seaweed. In terms of resilience, many cabins also adapt to the seasons through adaptive fenestration, flexible use of interior spaces, or the ingenious articulation of porches and annexes. Finally, from a socio-economic point of view, construction methods rely on the skills and autonomy of the Inuit. In summary, the organization of the camps and the architecture of the cabins derives from a mindful understanding of the territory and changing Northern conditions. As a result, cabins adapt and transform in accordance with both the environment and users' needs.

The study of camps along the Salluit fjord and interviews with local builders suggest that cabins' implementation, form and construction derive from an inherited sense of building and living on the tundra (Figure 44). These camps are composed on average of eight cabins that form compact linear clusters along almost the entire perimeter of the fjord. These cabins are often built on rocky outcrops located in small bays, against hills that protect from wind and waves. The most recent are built on, or were moved to, slightly elevated and easily accessible plateau (Figure 45). While avoiding the thawing permafrost, these locations also afford generous views of the fjord and the animals that cross it. In fact, the cabins' door and windows always face the fjord. Occupied by related families, the cabins are all located relatively close to the shoreline. The camps evolve in time, often over a few decades, by adding platforms and annexes transported by snowmobile. The initial pitched-roofed volume consists of a large living area. Sleep areas are at the back or in the annex, that is on the opposite side of the shoreline. The kitchen is always close to the entrance porch. Finally, the arrangement of recycled components and materials follows a craftsman's logic and sensibility, rather than their initial or prescribed use. The result is a variety of forms that echo desired qualities and cultural values. In brief, Nunavik cabins are an example of neo-vernacular architecture that reveals the considerable constructive ingenuity of the Inuit and its potential in contributing to the evolution of Northern villages.

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[94] Snowball, H and M-P McDonald (2020) Protecting Nunavik's cultural landscape. ARQ : la revue d'architecture, numéro thématique Habiter le Nord, mars, p. 11–13.

[95] Magnaghi, A (2014) La biorégion urbaine : Petit traité sur le territoire, bien commun. Paris, France : Rhizome.

Japan

Ainu and Chise

The Ainu are the indigenous people of Hokkaido and Tohoku Japan, and eastern Russia and China. Until recent years, they lived using their unique ability to coexist with the natural landscape of the northern regions they inhabit. The traditional Ainu residence is called *Cise* or *Chise*, but there are few research documents on *Chise*'s architecture and ways of living, since the Ainu did not have written language. In addition, much research on *Chise* is based on imagination and superstitious belief. The Ainu traditionally had, however, lived in cold climates with only natural building materials for centuries, and we can learn a number of things from their way of life and use of natural materials. In this report we first describe how the *Chise* is built. Next, we introduce the results of indoor environment measured in those *Chise*.

Chise is a simple wooden building made from natural timber from the surrounding forest. The structure of *Chise* is a hipped roof supported by *Hottate Hashira*, a pillar inserted into the earth.[96] The main building materials are wood and grass, but there are some examples with bark and bamboo as thatching material. As mentioned above, the Ainu did not have written language, but the building instructions for *Chise* has been communicated through oral stories, old paintings, and photographs taken in the late Edo and Meiji era. The *Chise* were also the target of extensive research in cultural anthropology in the 1900s.

In the old days, Fukuhei Takabeya published the two famous books, "Ainu no Seikatsu Bunka",[97] Life and Culture of Ainu, and "Ainu no Jyuukyo",[98] the residence of Ainu. In recent years, the studies on the building form of *Chise* by Koji Kobayashi[99] have been widely acclaimed. These studies contain many documents on how to build *Chise* and the lifestyle in *Chise*. However, they did not provide information on the thermal environment of the Chise.

'*Toi*' of *Toi-Chise* stands for earth. Some research indicates that *Toi-Chises* were constructed in Hokkaido. However, there are very few documents on *Toi-Chise* with the Sakhalin Ainu and Nibuhi people.[100, 101] In the literature, we can find photographs and figures of the pit house in Shikotan. The pit house seems to be mainly used as a bedroom in the winter season. We were able to identify only one comment about the living environments in *Toi-Chise*. According to the comment "the air quality in *Toi-Chise* was terrible. After the Spanish Flu, Ainu vanished away from their *Toi-Chise*."

As mentioned above, we can imagine the living environment from some documents on the life of Ainu in *Chise*, but there is a gap between their comments and the thermal environment estimated by the building style mentioned above. Kubota et al measured the temperature, the globe temperature, and the gas concentrations of CO_2 and carbon, for over 14 months in *Chise* being used by a small single-family.[102] The floor area of the *Chise* is 20 m^2, 4 ×5 m. The height to the beam is about 1.8 m, and to the rooftop is about 3.6 m. There are two ventilation holes at the top for a smoke window, 0.15 m^2 in total. Also, there is one window on the east wall and two windows on the south wall. The area of each window is about 0.4 m^2, 0.7×0.6 m. The wall thickness is from 27 to 42 cm for the roof and 10 cm for the wall. The walls and the roof were thatched with bundles of *Kaya*. The floor is covered with 2 or 3 layers of *Kaya* bundles and the mats are spread on it. In this study,

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[96] Endo Akihisa,1994,Hokkaido Jyuutakushiwa, Vol.1, Sumaino Tosyokan Syuppankyoku

[97] Takabeya Fukuhei, Ainu no Seikatsu bunka, Arusu, 1942

[98] Takabeya Fukuhei, Ainu no Jyukyo, Syokokusha, 1943

[99] Kobayashi Koji, Reconsideration on Architectural Culture of Ainu, Hokkaido Syuppan Kikaku center, 2010

[100] Kato Kyusaku, Culture of Gilyak recorded by Mamiya Rinzo, Bulletin of the National Museum of Ethnology 1(2),pp.305-333,1976/7

[101] Baba Osamu, Pit house of Karafuto Ainu "Toi-chise", Yearly report of 8 academic institute, vol.3, pp.121–133,1951/12

[102] Kubota Hideki et. al., Winter indoor environment in traditional house of Ainu "chise", Transactions of the Society of Heating,Air-conditioning and Sanitary Engineers of Japan, (41), pp.1–10, 1989/10

Construction of the roof

After ‘Chisepuni’, we constructed the wall

Figure 46. Construction of Chise and Toi-Chise.

	Thickness of roof and wall	Detail
Chise	Roof 30–45cm Wall 10–15cm	As shown in the middle right of Figure 45, the thickness of the wall between the bunch is thin.
Thermal retrofit Chise	Roof 30–45cm Wall 20–30cm	The thickness of the walls is doubled by installing the bunches on the inside surface.
Toi-Chise	Roof 30–45cm	

Table 3. Thickness of roof and wall.

Kubota et al. noted that the hearth generated very high temperatures in the *Chise*. Also, the indoor air turned smoky due to the recirculation of smoke from the hearth and with insuficcient ventilation.

In 1989, Usami et al. published the results of the investigation.[103, 104, 105, 106] They measured the thermal environment of two *Chise*. The floor area of *Chise* were 39 m^2 and 45 m^2, respectively. Roofs and walls were thatched with bamboo grass. In the studies, they reported that the temperature at the ground surface and 10 cm below were the same as the temperature below 30 cm which is always 2°C. They indicated that the thermal storage to the ground was effective in stabilizing the thermal environment of *Chise* and the effect was part of the cultural heritage of the Ainu people.

The results of the two research studies mentioned above were controversial for they had different views on thermal storage. In the Kubota et al. study, the floor surface was insulated and it indicated that the thermal storage did not influence the indoor thermal environment. On the other hand, the thermal storage caused by the continuous burning of firewood affected the thermal environment in Usami’s research.

In this report, we compared the thermal environment of *Chise*, the thermal retrofit *Chise* and *Toi-Chise* by measuring the surface temperature distribution by IR camera and the indoor room temperatures during our stay. We also measured the indoor temperature with a standard kerosene heater that measures the thermal output to analyze the thermal performance of *Chise* and to investigate the *Chise* lifestyle in the winter season.

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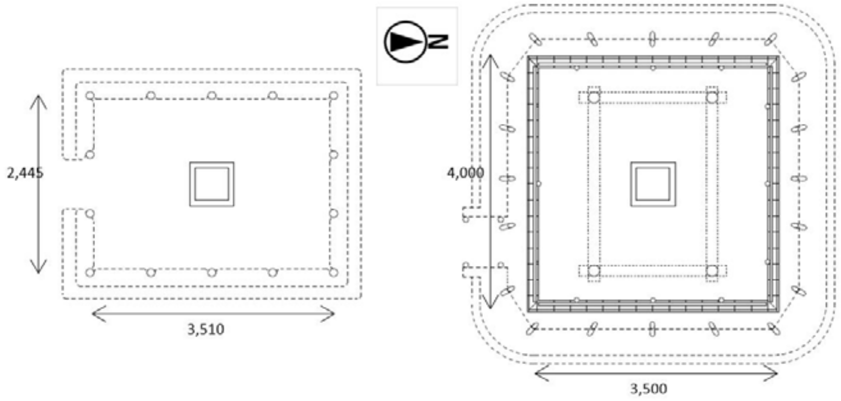
[103] Usami Chiwako et. al., A study on geothermal heat utilization to house through thermal conduction within the ground: 1)Thermal environment in the geothermal houses planned with following the thermal structure of traditional Ainu people’s house-chise, Summaries of technical papers of Annual Meeting Architectural Institute of Japan. D-2, Environmental engineering II,,2003, pp.643–644, 2003/7

[104] Usami Chiwako et. al., A study on geothermal heat utilization to house through thermal conduction within the ground, Underground temperature, Proceedings of AIJ Hokkaido Architectural Research Conference, (63), pp.165–168, 1990/3

[105] Usami Chiwako et. al. A study on geothermal heat utilization to house through thermal conduction within the ground: 2) Theory and measurement of thermal characteristics of house, Summaries of technical papers of Annual Meeting Architectural Institute of Japan. D-2, Environmental engineering II

[106] Nishizawa Takeo, Development of education program by reproduction of housing for northernindigenous peoplehttps://kaken.nii.ac.jp/en/grant/KAKENHI-PROJECT-22500872/



Plan of *Chise* Plan of *Toi-Chise*

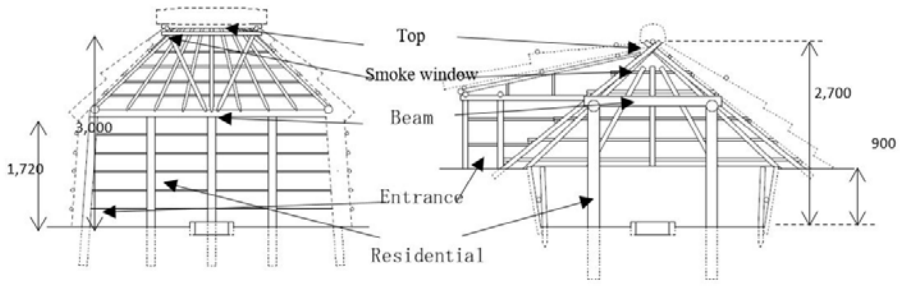


Figure 47. Plan and Section of Chise and Toi-Chise.
Mori Taro, et.al., Thermal Environment of Chise And Toichise in Winter Season, Journal of Environmental Engineering (Transactions of AIJ) 81(720), 189-197, 2016, Architectural Institute of Japan.

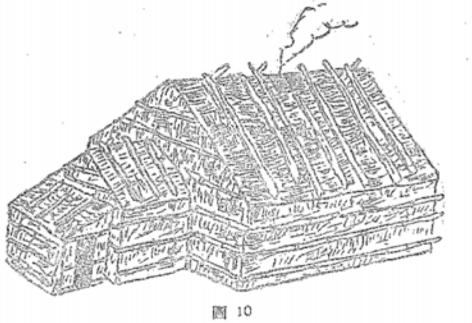


Figure 48. Insulation retrofit of Chise in Kafuto (Sakhalin).
Yamamoto Yuko, House for Karafuto Ainu, kenchiku Shinsho 10, Sagami syobo.

Construction of Chise and Toi-Chise

We implemented this research with the Grant-in-Aid for Scientific Research, “Development of Practical Educational Programs Using Arctic indigenous Dwellings”.[107, 108] Therefore, the construction work of *Chise* was carried out as part of the education program. We studied the literature and the local material for *Chise* before the construction. After that, we began the construction work at Kushiro National College of Technology on 26/4/2011 and completed it on 22/12/2011 as shown in Figure 45. We constructed *Chise* manually with no construction machines. It took about 164 person-days to finish the work.

Figure 46 shows the plan and section of each *Chise*. The floor area of the constructed *Chise* was 2445 mm wide and 3510 mm long. The height of the beam was about 1720 mm. The hearth, 320 × 280 mm, stands at the center. We did not construct Sem, the space for the entrance.

Insulation retrofit of Chise

After the construction of the above *Chise*, we measured the room temperature distribution and CO_2 concentration during the overnight stay in the winter season 2011. We were not able to safely stay in the *Chise*, due to the high infiltration rate from the bottom of the wall. Therefore, we decided to retrofit the additional insulation before the measurement in December 2012. That insulation work was described in “Karafuto Ainu no Jyukyo” [109] published in 1943 as shown in Figure 48.

Door: We used the reed screen for the usability before the retrofit. The three layers of *Kaya* with a 10–15 cm diameter were used for insulation and air-tightness.

Wall: We installed just one layer of *Kaya*, 10–15 cm, outside the wall structures before the retrofit. Another layer of *Kaya*, 10–15 cm, inside the wall, was installed to double the wall thickness for insulation and air-tightness.

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[107] Nishizawa Takeo, Construction of housing for northern indigenous people(toichise) and Comparison of thermal environment, https://kaken.nii.ac.jp/en/grant/KAKENHI-PROJECT-25350272/

[108] Yamamoto Yuko, House for Karafuto Ainu, kenchiku Shinsho 10, Sagami syobo

[109] Ibid

Construction of Toi-Chise

We built the *Toi-Chise* in 2013. The literature surveys were carried out before the construction. However, just two studies[110], were found. The Ainu in Hokkaido had already given up the *Toi-Chise* in the first half of the Tokugawa era, the 17th century, in Japan. The literature investigated *Toi-Chise* in Sakhalin Ainu. The plan view and the sectional view are shown in Figure 49. Also, we found some pictures of *Toi-chise* in Sakhalin in Hokkaido University Archive System as shown in Figure 50. The document indicated that *Toi-Chise* was a pit-dwelling. Therefore we visited the Oonaka ruin which restores the same type of dwelling to study how to build *Toi-Chise*.

First, they remove the supporting wood for roof and wall cover. After that, they cover the roof and walls with dried grass and re-install the support. Also, they made the second cover-shed for entrance. The shed had two entrances. They used the leeward entrance to avoid infiltration.

Measurement of a thermal environment

After the above construction process, the thermal environment, including inside temperatures, globe temperature, and surface temperatures were recorded by IR camera during the one-night stay in January 2012, December 2012, and December 2013. Figure 51 shows the outside air temperature and wind speed measured at AMeDAS station (Shiranuka, altitude 9m) in each period. The outdoor environments are as follows.

1) The lowest outside air temperature was recorded each time. The temperature was under –15°C from 3 AM to 6 AM. Also, insulation and air-tightness were poorer than in other cases. We felt most cold in this case.

2) The lowest outside temperature was about –10 °C when we measured the Insulation retrofit *Chise*.

3) The outside temperature was about 3 °C in *Toi-Chise*. The wind velocity in the measurement of *Toi-Chise* was much higher than that in the above cases.

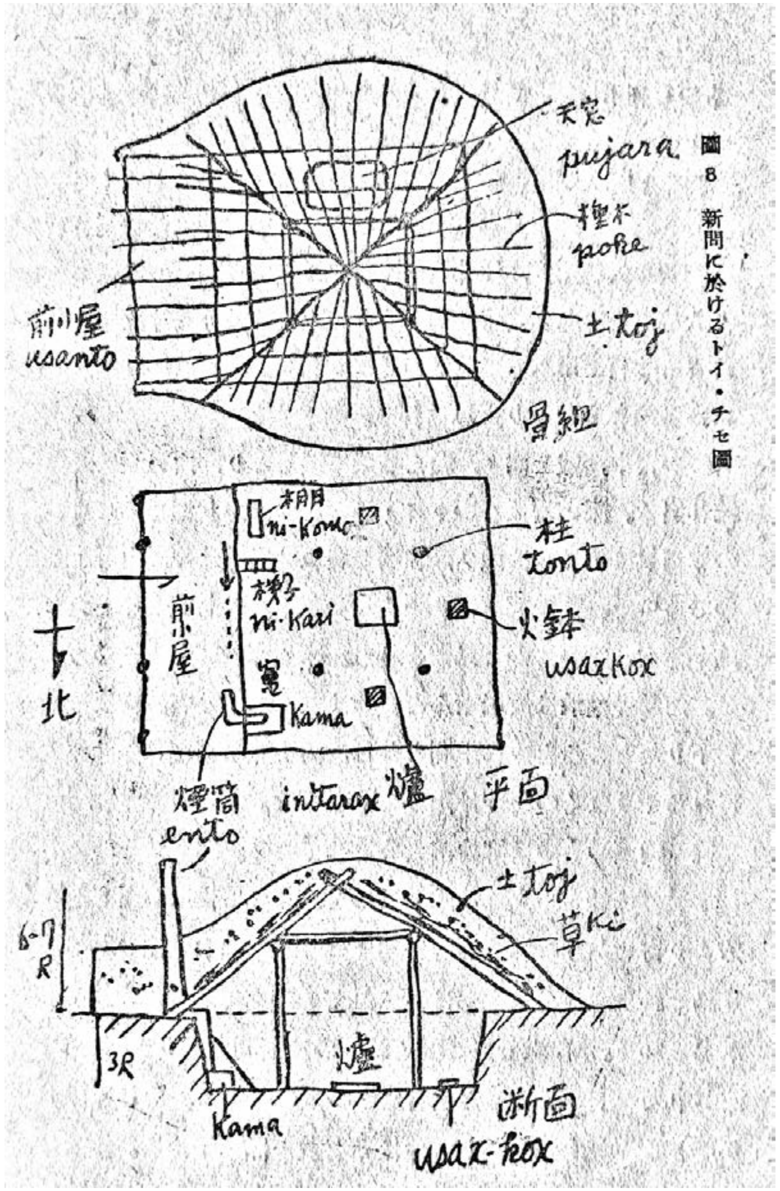

Figure 49. Sketches of Toi-chise in Karafuto.
'Karafuto Ainu no Jukyo".

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[110] Enai Masamichi et. al.,RESEARCH ON THE DISTRIBUTION OF ROOM AIR TEMPERATURE AND THE HEATING LOAD IN THE OCCUPIED SPACES : Part–1 Response of living to the coldness and the varying patterns of room air temperature, Transactions of the Architectural Institute of Japan,264,91–98,1978

Figure 50. Pictures of Toi-chise in Karafuto. *Hokkaido University Archives. https://www2.lib.hokudai.ac.jp/hoppodb/contents/photo/l/0B062030000000164.jpg*

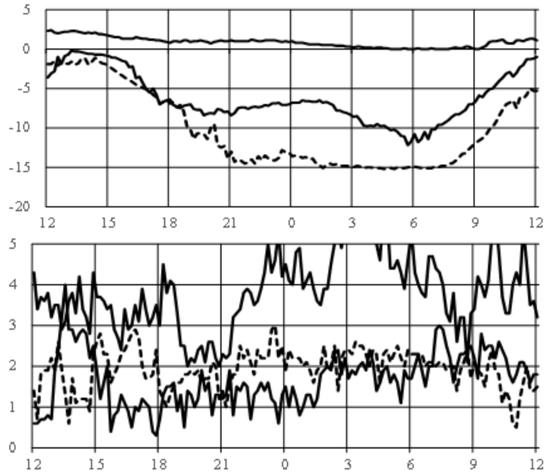


Figure 51. Climate during the measurement.

Measurement of Chise

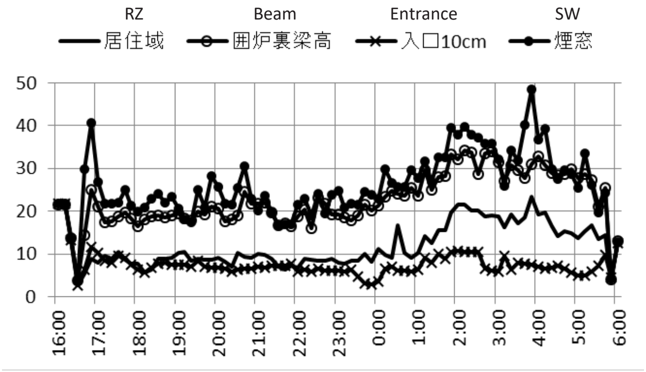
The measurement was carried out from 13:00 on January 19 to 8:50 on January 21 in 2012. The room was pre-heated with the electric heater, about 1000 W, before the measurement. We stayed in *Chise* and used the hearth as a heater during the night on 20–21, Jan. The six-member group participated in the measurement. The recorded temperatures are shown in Figure 46.

Measurement of insulation retrofit Chise

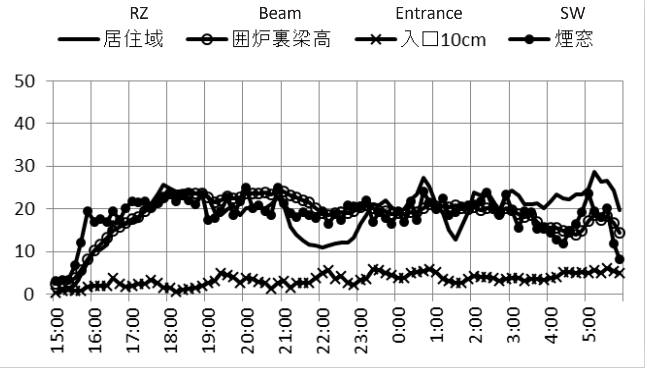
After the insulation retrofit, we implemented measurements of the thermal environment in the insulation retrofit *Chise*. The measurement period was from 15:00 on December 21 to 6:00 on December 22, 2012. The number of participants was also six. In this case and the next case, we did not preheat the dwelling, as it was ineffective. In addition, we discovered a document indicating that the Ainu used *Kaya* and straw as a carpet in the winter season. Then we used EPS 25 mm board for the ground insulation.

Measurement of Toi-Chise

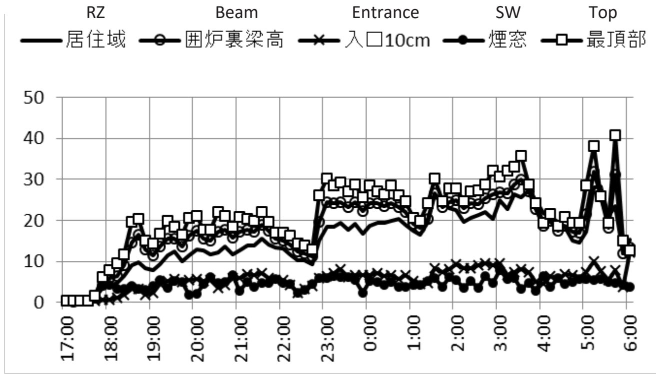
The measurement of *Toi-Chise* was carried out from 15:00 on December 20 to 6:00 on December 21, 2013. The number of participants was also six. We measured CO_2 and carbon concentration in addition to the above measurement for safety.



1) in Chise



2) in Insulation retrofit Chise



3) in Toi-Chise

RZ: Residential Zone

SW: Smoke window

Figure 52. Change of in-out temperature differences.

Temperature difference between inside and outside

Figure 52 shows the differences in indoor-outdoor temperatures. Although the overall heat-loss coefficients of each *Chise* were different, the temperature at the entrance, which supplies combustion air to the hearth is about 0 to 10°C. The temperature around the top area is about 20°C or more. In other words, there is a considerable temperature difference over 20°C in a small space. This indicates that the indoor climate qualities of those spaces are remarkably poor.

In the case of *Chise*, the burning firewood caused the infiltration from the gap between the wall and the floor. The temperatures in the residential area did not rise at all until 23 o'clock. After we put about three times as much firewood as before from 0 - 1 AM, we were able to keep 5°C. On the other hand, in the case of the Insulation retrofit *Chise*, we covered the bottom of the wall with snow to stop infiltration. The temperature of the residential area rose immediately after putting the fire firewood. Also, the temperature difference between the residential area and the top area was much smaller than that in the *Chise*. The temperature was much lower than in modern houses. The retrofit insulation and airtightness improved the temperature in the residential zone.

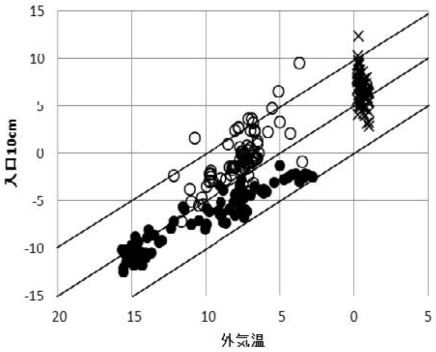


Figure 53. Relationship between outdoor temperature and bottom temperature.

As shown in Figure 56, 2/3 of the heat loss in the *Chise* was caused by infiltration. The measurements led us to assume that the Ainu had developed some method to prevent infiltration. However, with the use of this method, there is a risk of dangerous levels of combustion gases due to lack of ventilation. The document has the following description. "In Matsumae prefecture in Hokkaido at the end of Edo era, there are reports of many skin diseases caused by burns and eye diseases caused by combustion gases due to insufficient ventilation in winter." Japanese people first came to Hokkaido with their traditional housing style. Their unfamiliarity with the *Chise* caused such diseases. We believe that the Ainu who lived in Hokkaido for a long time had knowledge about proper methods for heating with hearth.

The temperature difference of *Toi-Chise* was different from the other two *Chise*. The temperature difference gradually increased after burning firewood. The outside temperature was about 0°C. Therefore, the heat capacity of the soil influenced the transition of the temperature difference. Also, the temperature of the smoke window which rose in the former cases did not rise at all. It seems that there was wind blowing into *Toi-Chise* from the smoke window because the external wind velocity was much higher than in former cases in the measurement day. Even in these circumstances, the upper and lower temperature difference was less than 10 °C.

Figure 53 shows the correlation between the outside air temperature and the inlet temperature measured at the entrance, 10 cm above the ground. In the case of *Chise*, the points are located in 0 – 5 °C area than the outdoor temperature. In the case of insulation retrofit and *Toi-Chise*, the points are located in over 5 °C area. Since the doors were not airtight, preventing the infiltration from the entrance was difficult. However, the method such as insulation retrofit and *Toi-Chise* were effective for improving the thermal environment in *Chise*.

Indoor surface temperature

We took the IR images during each stay every hour. Figure 54 shows the IR images in each case when the temperature differences were big enough. The outside temperature in *Chise*, thermal retrofit *Chise*, and *Toi-Chise* were –13°C, –6°C, and 1°C respectively. The temperatures near the floor were low and the temperatures in every top zone were high in every case. The temperature differences within a space are about 20°C. The simple comparison among the cases is difficult because we put the firewood which varies in size, water contents, etc. to remove cold at a different pace. However, the temperature distribution in *Chise* was remarkably lower than in other constructions. The area under –10°C distributed around the bottom of the wall because the cold infiltration came from the outside by the low pressure caused by the hearth. Also, the outside environment was more than 10°C lower than those in other cases. The temperature distribution even in the top area was under 10°C.

The insulation retrofit *Chise* improved the airtightness in the bottom area. There was no area under 0°C in this space. In the case of *Toi-Chise*, although there was no snow for preventing the infiltration, the bottom area where the infiltration comes from was over 5°C. The temperature around the ceiling was high because of thick insulation, and the thermal radiation increased temperatures in the bottom area as well. In conclusion, floor insulation is useful to keep all space warm using heat radiation.

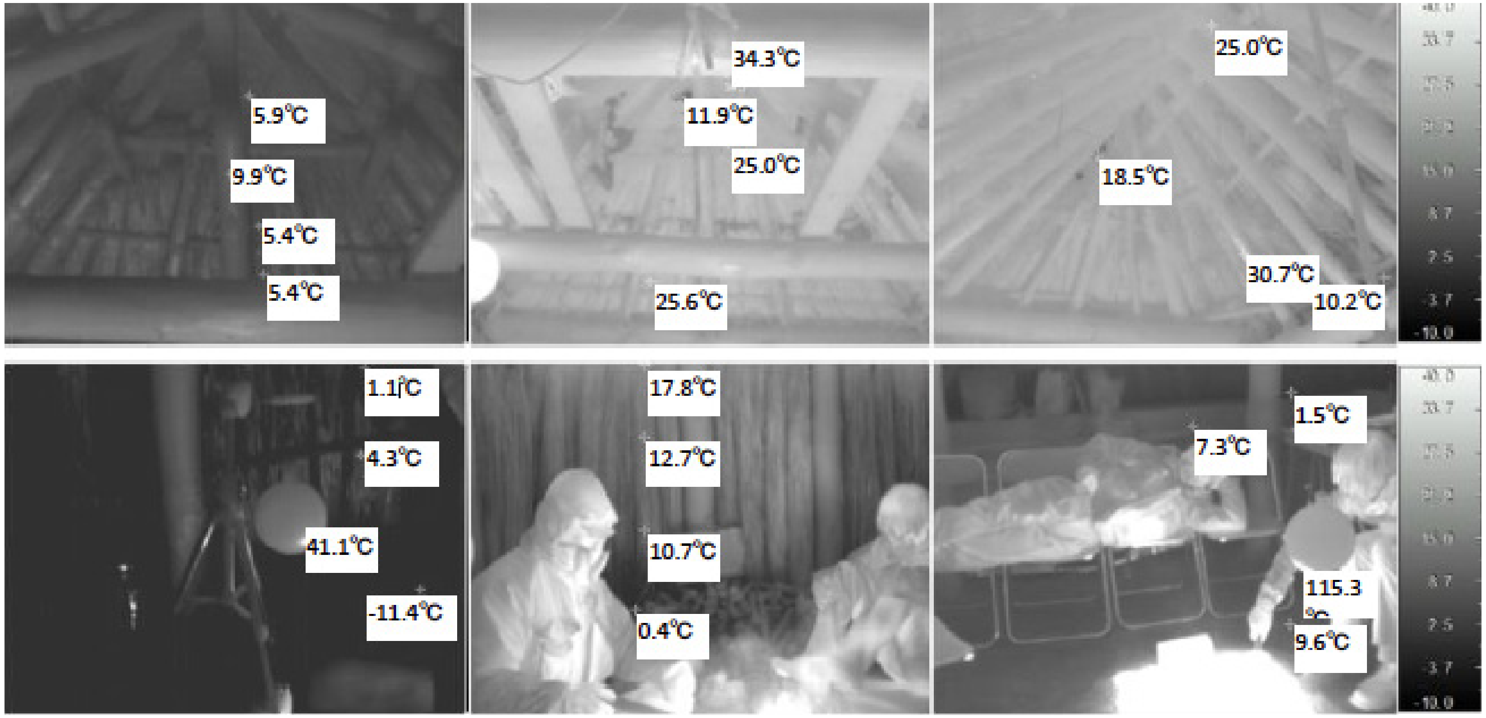


Figure 54. IR images during measurement. 1) thermo view of Chise 2) thermo view of Chise with insulation retrofit 3) thermo view of Toi-Chise.

Comparison of Thermal Environmental with Standard Heater

In the previous section, we introduced the results of measurements when we spent a night in each *Chise*. However, it was difficult to compare the thermal environment of the different *Chises*. We used the portable kerosene heater to estimate the heating rate and ventilation with fuel consumption. Also, we are able to identify the overall heat loss coefficient of *Chise* as shown in Figure 54. Researchers usually use an electric heater as a heat source when they measure a thermal environment.[111] However, the hearth in *Chise* sometimes generates more than 10 kW. A regular electric heater with a regular electric plug cannot release this heat.

The measurements were conducted on cloudy nights in April and May in 2015 to avoid solar radiation and nocturnal radiation as much as possible. We simultaneously measured kerosene combustion in the thermal retrofit *Chise* and *Toi-Chise* by measuring the weight of the heater every hour. The snow had already disappeared in the measurement period. Then, the airtightness of insulation retrofit *Chise* was almost equivalent to that of *Chise* because insulation retrofit *Chise* had the gap in the bottom of walls when the measurements were take. In other words, we measured thermal retrofit *Chise* as general *Chise*. The heating rate was calculated with equation (2). Also, kerosene emits carbon dioxide when burning. The ventilation rate was estimated by measuring CO_2 concentration in the steady-state as shown in equation (3) and equation (4). The heat-balance equation can be divided into the heat transition loss and ventilation loss by equation (1) when the ventilation rate was identified. Finally, we can compare the overall heat loss coefficient of *Chise* and *Toi-Chise*.

$$\bar{H} + (\overline{KS} + c\rho Q)(\theta_o - \theta_i) = 0 \qquad (1)$$

$$\bar{H} = \frac{(w_s - w_e)k_1}{\Delta T} \qquad (2)$$

$$k_2 = \frac{(w_s - w_e)k_3}{\Delta T} \qquad (3)$$

$$Q = \frac{k_2}{(p_i - p_o)} \qquad (4)$$

H: Heating rate[W]
$\overline{KS}$: Overall heat-loss coefficient [W/K]
c: Specific heat of air[J/kgK]
ρ: Density of air [kg/m^3]
Q: ventilation rate [m^3/s]
θ_o: Outdoor temperature
θ_i: Indoor temperature [℃]
w_s: Weight at the start
w_e: Weight at end[kg]
ΔT: Time of measurement [s]
k_1: LHV[J/kg]
k_2: CO2 emission[kg/s]
k_3: Unit emission of CO₂[m^3/kg]

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[111] Enai Masamichi et. al.,RESEARCH ON THE DISTRIBUTION OF ROOM AIR TEMPERATURE AND THE HEATING LOAD IN THE OCCUPIED SPACES : Part-1 Response of living to the coldness and the varying patterns of room air temperature

Figure 55 shows the difference of temperature and CO_2 concentration in the measurement. All measurements were carried out for over 2 hours to reach the steady-state of the temperature and the carbon dioxide concentration. As shown in Figure 55, both values reached a steady-state in about 30 minutes. The average values in the steady-state were substituted into equation (1) – (4) to estimate the overall heat-loss coefficient.

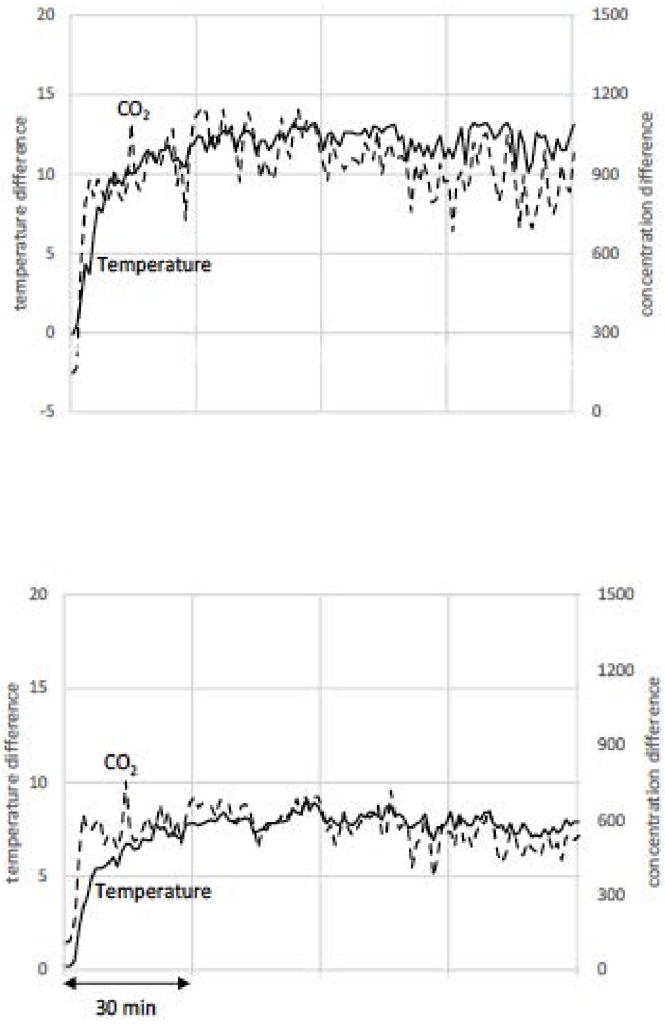

Figure 55. Transition of temperature difference and CO_2 concentration difference.

Figure 56 shows the relationship between ventilation loss, heat transmission loss, and heating rate. In a building like *Chise*, which has many gaps, an increase in heating causes an increase in infiltration due to the buoyancy flow from the hearth. Therefore, the ventilation losses were increasing when heating rates were increasing in the case of insulation retrofit *Chise* in Figure 56. Also, the ventilation losses in insulation retrofit *Chise* were about twice as those in *Toi-Chise*. The heat transmission losses in *Chise* were almost equivalent to those in *Toi-Chise*. It implies that the overall heat-loss coefficient of *Toi-Chise* was better than that of *Chise*, especially due to the airtightness which prevents infiltration. The wall structure of *Toi-Chise* decreased the gap between the wall and the floor. The insulation retrofit with snow and *Toi-Chise* were effective at achieving a low overall heat-loss coefficient.

The overall heat-loss coefficients of *Chise* and *Toi-Chise* were about 600 and 900 W/K respectively. Both *Chise* need about 20kW or more to keep the indoor temperature at 10 °C when the outdoor temperature is –20 °C. These measurements imply that ventilation loss could be bigger when the temperature difference increases. It is difficult to generate sufficient heat in these spaces in a firesafe way while maintaining a good indoor air quality. Therefore, we are convinced that the Ainu installed more insulation and had means such as clothes and foods to survive in the severe winter season.

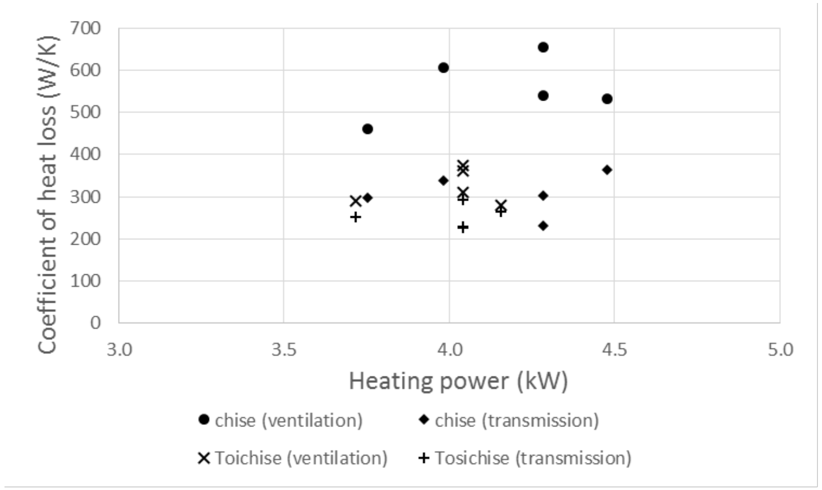

Figure 56. Relationship among ventilation loss, heat transmission loss, and heating rate.

4. OVERVIEW OF BUILDING STOCK AND REGULATION

(in Finland, Canada and Japan)

Finland

The goal was to analyze the carbon footprint from the Northern Buildings, Finland, including all relevant types of buildings and their annual energy consumption.

Northern and Arctic Finland contains four municipalities: Inari, Enontekiö, Utsjoki and Sodankylä. These municipalities have 18 297 inhabitants and building stock with 1 952 259 floor-m^2. 20% of the population are Sámi. In order to ensure a balanced representation, several criteria were considered, including population, total floor area per building type, common building structures (facade and load bearing structure), heating systems and fuel types used, carbon footprint for the energy consumption.

Cultural variation and the effect this may have on energy consumption has not been taken into account in the study.

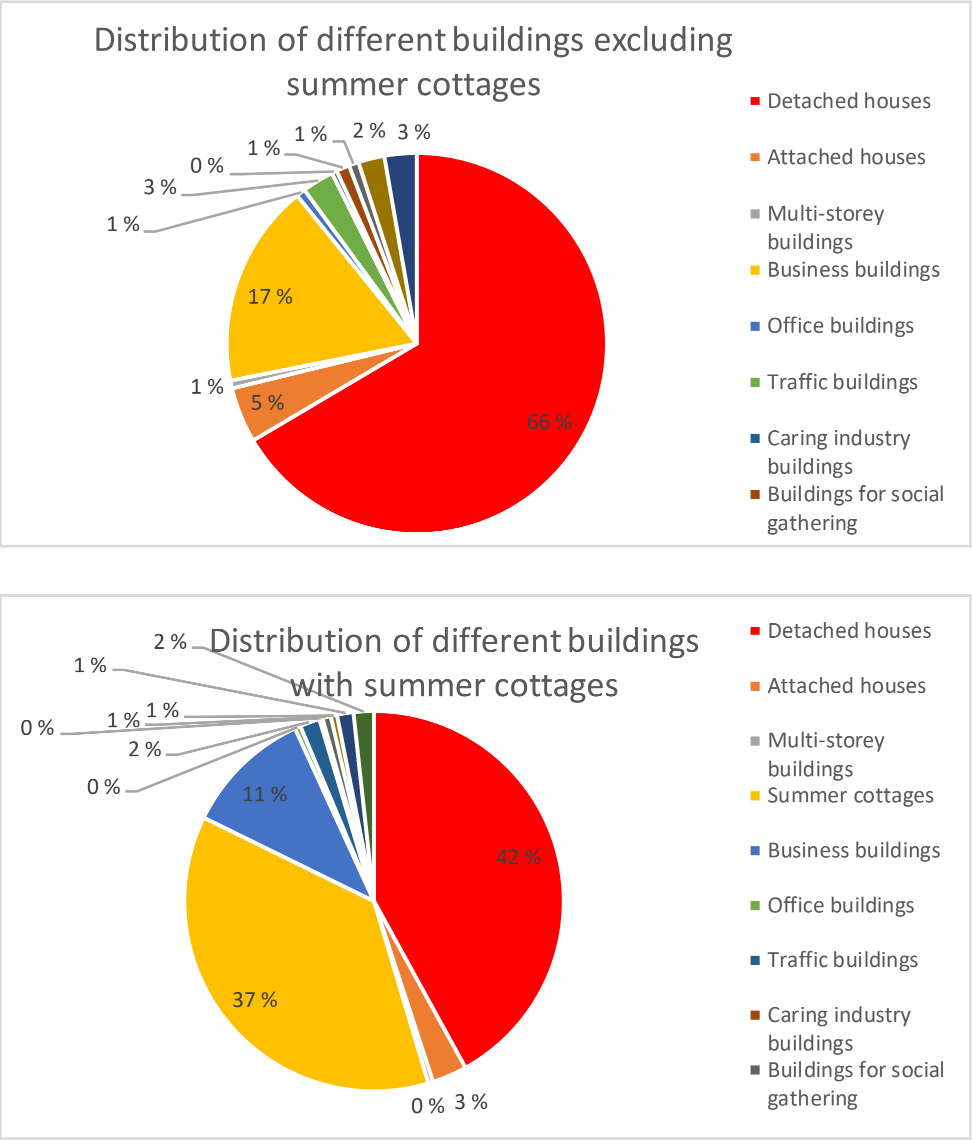

Figure 57. Distribution of different building types excluding and including summer cottages in Arctic Municipalities, Finland.

Country-specific building data classifies buildings by their type and age. It is based on statistical data on buildings and summer cottages acquainted from Statistics Finland and Population Register Center Finland.[112] [113]

The most common building type is the detached house (42%) followed by summer cottage (37%).

The highest number of buildings was constructed during 1980–1989.

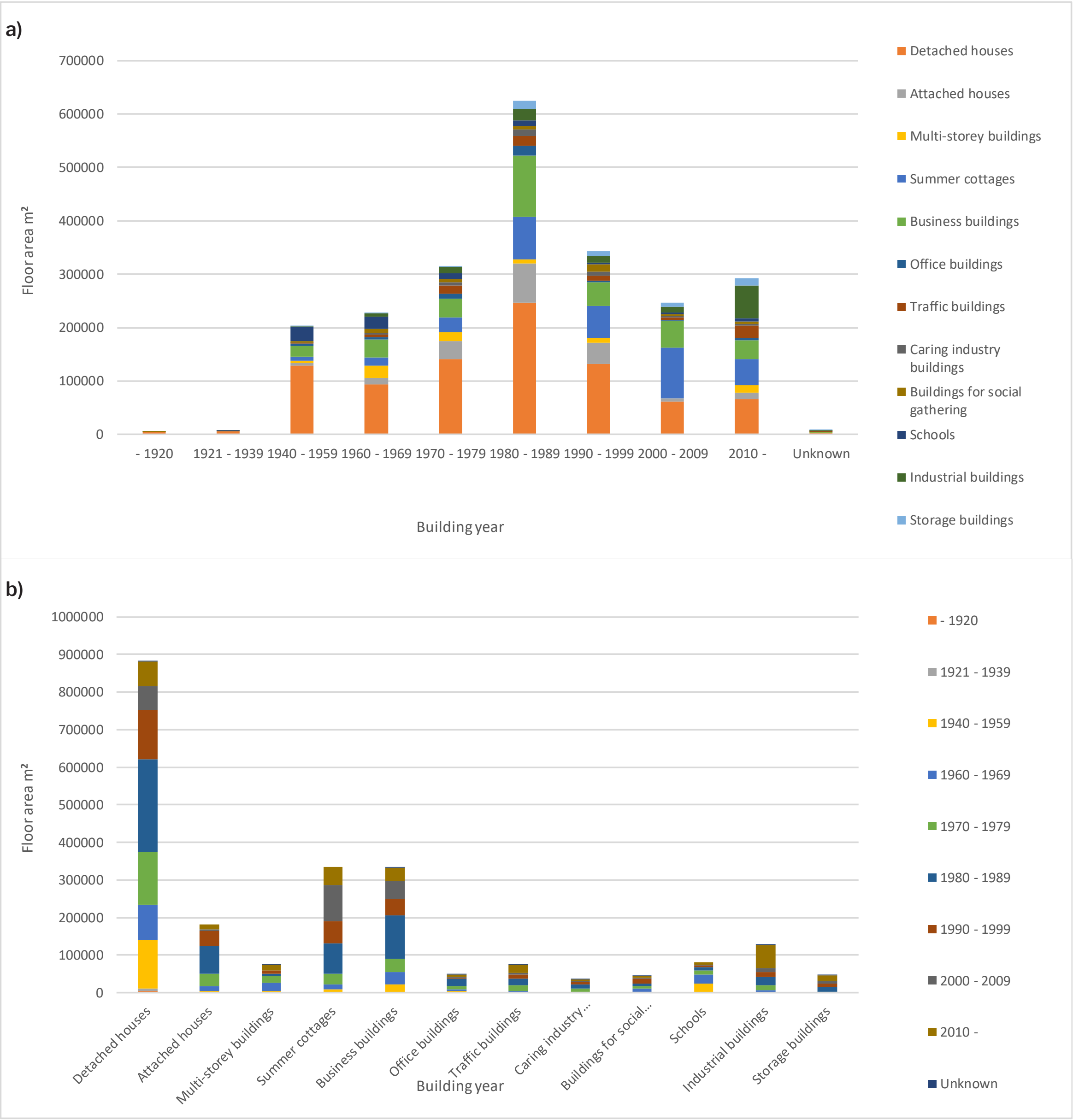

Figure 58. **a.** Building type and floor area by construction year, in Arctic Finland. **b.** Floor area and construction year by building types, in Arctic Finland.

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[112] Statistics Finland (Suomen virallinen tilasto (SVT): Rakennukset ja kesämökit [e-publication]. ISSN=1798-677X. Helsinki: Tilastokeskus [cited: 16.10.2019]. http://www.stat.fi/til/rakke/index.html.

[113] Building and dwelling information from Finnish Liiteri-database: https://liiteri.ymparisto.fi/ Data based on Population Information System, Population Register Center, Finland 2018 (Väestötietojärjestelmä, Väestörekisterikeskus, 2018).

Load bearing structures

Main load bearing material is wood. However, in the building type “attached house”, the main load bearing material is concrete.

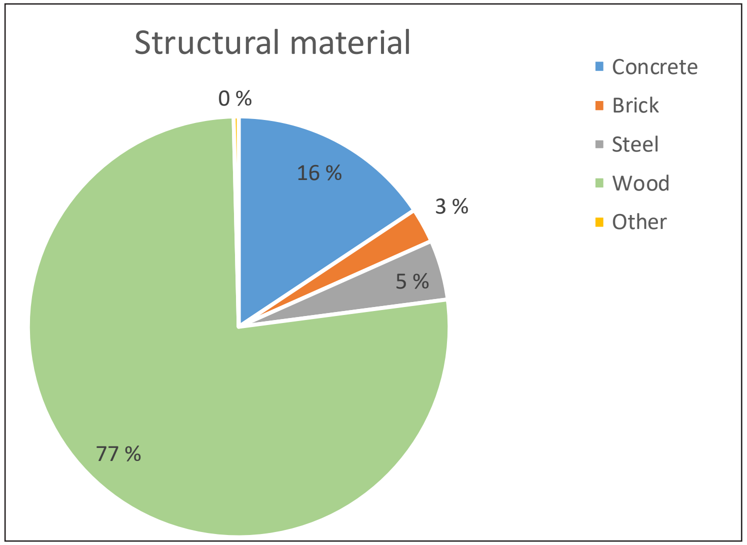

Figure 59. Load bearing material types used in Arctic Finland.

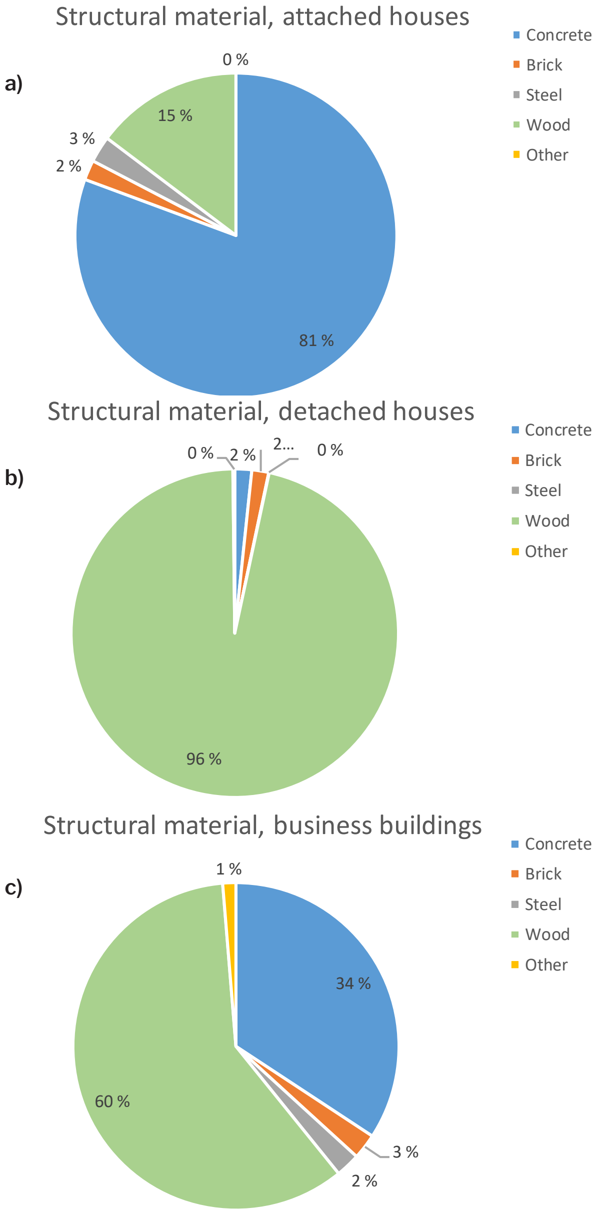

Figure 60. Load bearing materials in attached **(a)**, detached **(b)** and business type buildings **(c)**, Arctic Finland.

Facades

Main facade material is wood. However, in the building type ”attached house”, the main facade material is concrete.

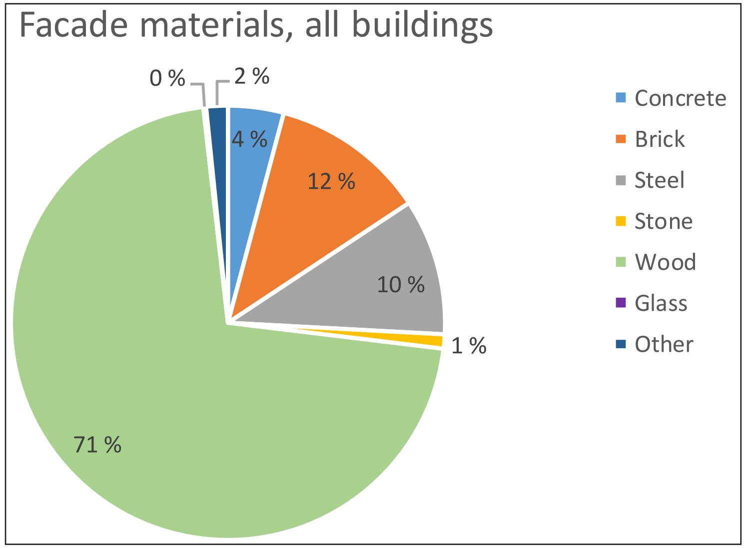

Figure 61. Facade material types, Arctic Finland.

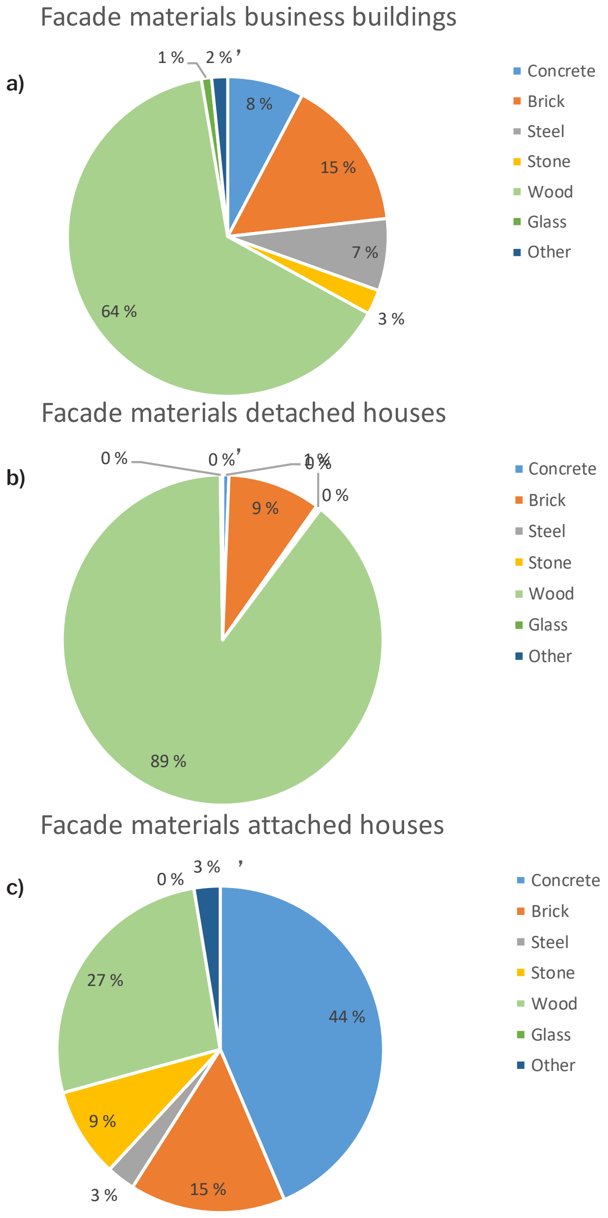

Figure 62. Facade material type in attached- (a), detached (b) and business building types (c), Arctic Finland.

Heating systems

Electric heating is the main heating type in Arctic Finland.

Heating system according to the construction moment registered (not including changes in the heating systems, which were possibly made during the use phase refurbishment).

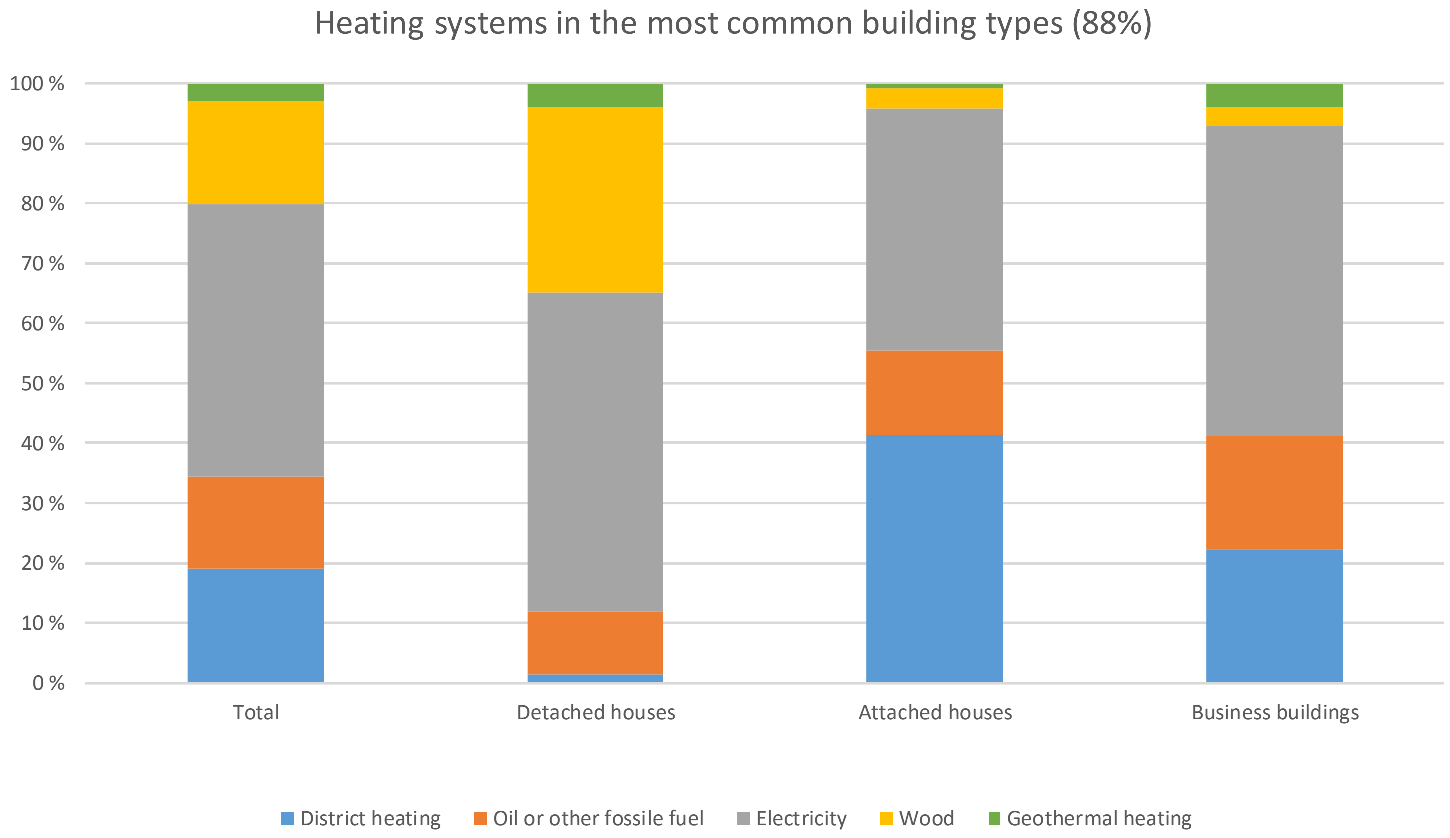

Figure 63. Heating systems in most common buildings, in Arctic Finland.

Heating consumption

Average heating consumption in assessed regions is 200–230 kWh/m^2 while CO_2e is 44–56 $kgCO_2$/gross floor-m^2.

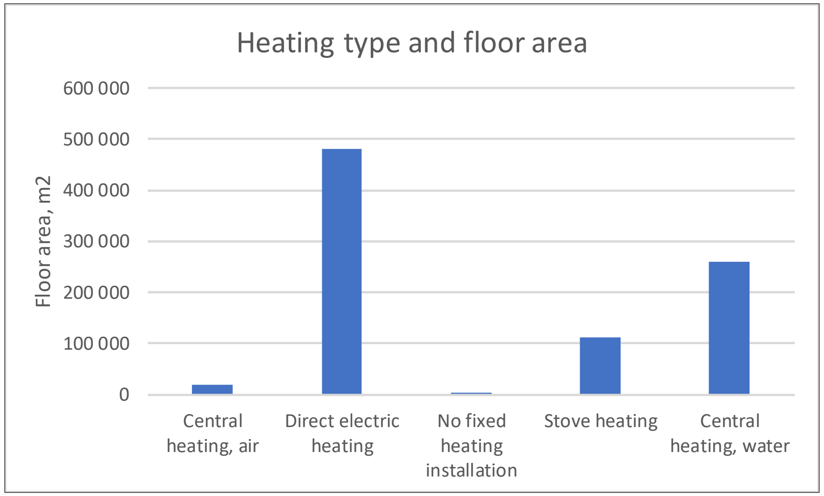

Figure 64. Heating type by floor area, in Arctic Finland.

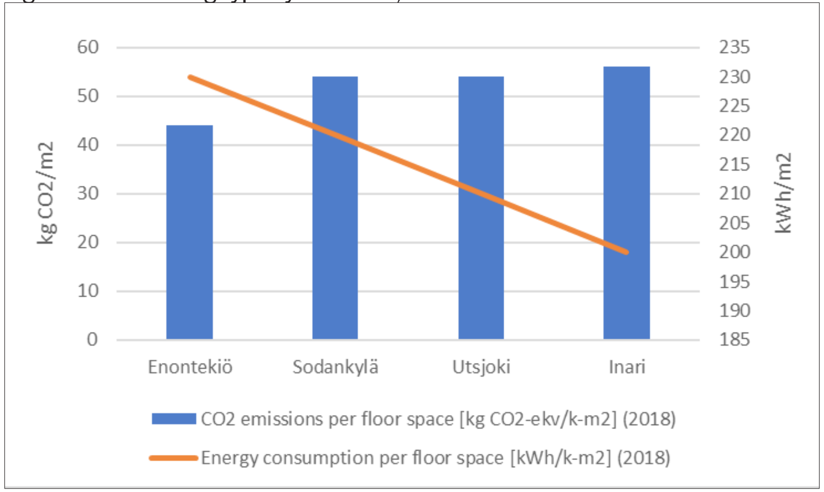

Figure 65. Used fuel type (a) and carbon footprint (b) from heating, Arctic Finland.

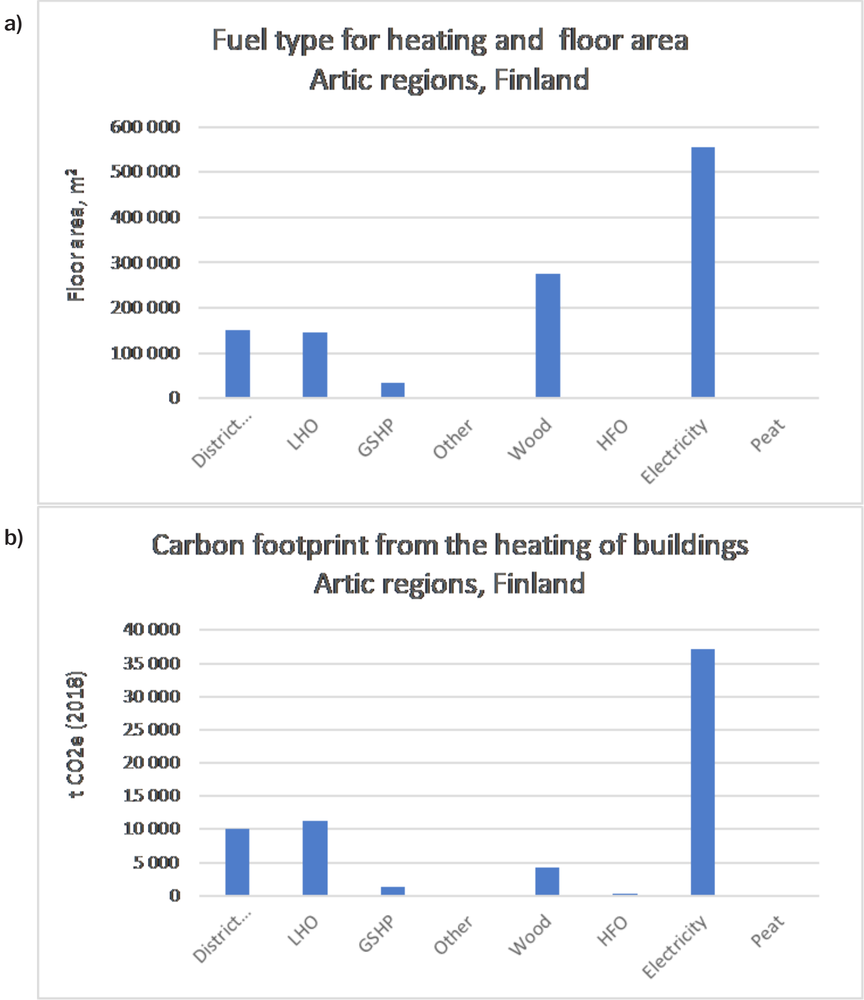

Figure 66.

Regulation

In Finland, building regulations require that the building has to be designed and built to use energy and natural resources wisely. The minimum requirements for energy-efficiency must be verified with calculations.

At the time of writing this report, Finland is taking steps towards regulating buildings' full life-cycle impacts. The Ministry of the Environment's low-carbon construction roadmap published in 2017 strives to incorporate the carbon footprint of buildings into the legislative framework. As part of this roadmap, Finland has developed a national method for assessing the carbon footprint of buildings, which is in a testing-phase with real construction projects. The method for assessing the carbon footprint of buildings aims to help the calculation of the climate impact of construction, and it covers a building's entire life cycle from manufacturing of building products to transportation and construction site operations, use and repairs, and demolition and recycling at the end of the life cycle.

In line with the Government Programme of 2019, the aim is that the legislative framework will be in use in the mid-2020s.

Conclusions

- According to estimates, the population in the Arctic area decreases by approx. 3 percent every ten year.

- The main building type is the detached house (66%). When summer cottages are taken into account, the two most common building types are detached houses (42%) and summer cottages (37%).

- Highest number of buildings was constructed during the years 1980 – 1989.

- Main load bearing material is wood. However, in the building type “attached house”, the main load bearing material is concrete.

- Main facade material is wood. However, in the building type ”attached house”, the main facade material is concrete.

- Main heating type in the assessed municipalities was direct electric heating.

- Out of all heating types, electric heating is the largest source of carbon emissions, although electricity production in Finland causes rather low unit based carbon emissions (kg/kWh).

Northern Governance & the controversial history of housing initiatives in the North

A primary factor influencing the development of governance systems in the North is the distinctive relationship the territories maintain with the government of Canada. Under the Constitution Act, 1871, Canada took responsibility for the administration, peace, order and good government of the territories. While provinces get their powers from the Constitution, territorial governments are delegated powers through legislation, since these were not included at the time of its drafting. Historically, in the North, Federal institutions in Canada had jurisdiction over responsibilities normally assumed by provincial governments, since Ottawa served as the legislative capital in the North. Starting in the 1950's, a process of devolution or transferring responsibilities (e.g., education, health, housing, social services) got underway as that was a shared goal of both the territorial and federal governments. The devolution process, related to land & resources management, and the transferring of responsibilities have only recently been resolved (Yukon in 2003; NWT in 2014) or are still on-going (Nunavut), which resulted in poor housing initiatives ill-suited to northern climates and Northerners' needs and ways of life.

Since they are constituents of provinces, Nunavik and Nunatsiavut have a different governance regime. The region now occupied by Nunavik was officially transferred to the province of Québec in 1912. The first matchbox houses provided by federal programs in the late 1950s and early 1960s were poorly suited to Inuit practices.[114] In 1981, after the James Bay and Northern Quebec Agreement, the federal government transferred housing responsibilities to the province. Through its social housing program, the Société d'habitation du Québec (SHQ) mostly provided detached single-family houses to local populations. Following the federal government's withdrawal, very few houses were built between 1995 and 1998. By 1999, the newly founded Kativik Municipal Housing Bureau (KMHB) was managing the residential stock. Since 2000, both governments are involved in housing production: while the federal funds Makivik Corporation to build houses (mostly consisting of semi-detached houses or duplexes), the SHQ funds KMHB to manage the park. The SHQ also finances the renovation of existing houses, as well as the gap between collected rents and the actual cost of operation. Through its Plan Nord, the Quebec government has also pledged the construction of 300 units by 2016. Finally, the responsibility of the Kativik Regional Government (KRG) is to determine the number of houses to be built each year[115]. All of these authorities' involvement in the production of housing in Nunavik follows a history of long-standing local concerns ranging from an insufficient number of units to answer pressing needs, overcrowding, premature construction problems, a lack of variety in housing types and tenure to better fit Inuit aspirations and cultural practices, and the possibility of participating more directly in the design, construction and overall decision-making[116]. That said, the SHQ / KMHB homeownership and recent "rent-to-own" programs are slowly taking off.

Labrador and Newfoundland was the last province to join the Canadian Confederation, in 1949. The Inuit of Nunatsiavut signed the Labrador Inuit Lands Claims Agreement with governments in 2005, which resulted in the creation of a self-governance Inuit regional government. The Nunatsiavut government is now directly involved in policies related to housing.

Sheppard and White (2017) divide the history of housing initiatives in the North into three periods; 1910–60,

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[114] Duhaime, G (1985) ibid.

[115] Therrien, A and G Duhaime (2017) Le logement social au Nunavik, pouvoirs et responsabilités. Recherches amérindiennes au Québec, 47(1), 101–110.

[116] Ikey, O and L Yeates (2016) Les problèmes de logement au Nunavik, quelques faits. Mémoire présenté au Comité sénatorial permanent des peuples autochtones, Ottawa. https://sencanada.ca/en/Content/Sen/committee/421/appa/52586-e. Consulté le 3 mai 2019.

1960–90, 1990 to today. The turn of the 20th century marked a dramatic change in the architectural landscape of the North. As Sheppard & White report:

“the advent of imported architecture is marked by the outpost structures that emerged in the 1910s. Trading posts, missions, and military installations were strategically sited based on larger territorial and logistical factors. They were often built near valuable trading resources, strategic military points, or coastlines [...] As outposts spread across the North, they catalyzed permanent settlement among Aboriginal people, who sought out these places for the job opportunities rather than for housing. With this came the desire for something that had never existed nor ever been needed: a year-round dwelling”.[117]

Up to the 1950s, and given this inherently new need for stationary year-long housing structures, Northerners “began to assemble informal structures from construction waste and scrap materials” around the outpost structures, in what is commonly referred to these days as shacklands; an architectural form still prevalent today across many coastal communities in the North and, according to architect Joshua Armstrong, underappreciated as a form of early vernacular architecture in the North.[118] Yet, given that the perceived poor housing conditions in the North were often identified as a leading cause of increased illness the Federal government undertook, in 1959, its first housing initiative in the North: “the Eskimo Housing Loan Program”.

The program set about tackling housing shortages across these newly formed sedentary communities. The focus on quantity over quality throughout the program’s 10-year life cycle was clear, and would remain a staple of federal housing programs to this day.

“The units offered through this rental-purchase plan were prefabricated plywood dwellings of under 300 square feet, nicknamed “matchboxes” because of their modest size and simple shape. This rudimentary structure was simply the outcome of building entirely out of engineered plywood: the four-by-eight-foot sheets made up the entire 12-by-240-foot floor plan. The matchbox had no running water or sewage treatment and, despite its small size, housed multi-generational families—sometimes as many as 20 inhabitants [...] The intent was just to provide something that qualified as a shelter. The matchbox [...] may not have offered much in the way of design, or even, architecture, but they were an inevitable modernizing [colonialist] force”.[119]

After its cancellation in 1965, the subsequent iteration of the “Eskimo Housing Loan Program”, the “Northern Rental Purchase Program”, sought to create three bedroom dwellings, which “helped to solve issues of affordability, although quality of life remained neglected”. In fact, dwellings were often described as “drafty, cramped, unsafe and totally unsuited to the northern lifestyle”. [120] Up to the 1990’s, all housing initiatives in the North remained plagued by an emphasis upon simple rudimentary designs meant for subsistence, “designed on a pattern suited to southern Canadian suburbs”.[121]

As mentioned before, a process of devolution and transferring of responsibilities had been initiated in the 1950’s. Prior to that, the Federal government in Ottawa has retained control over housing initiatives in the North. As more and more territorial housing corporations were formed, initiatives became more inclusive and held real considerations for Northerners’ lifestyles and needs. Several projects across the Canadian North are good examples of this new architectural vernacular.[122] However, these projects relate mainly to schools, cultural centers and governmental facilities, as little progress has been made within the residential sector in the North.

The housing crisis remains at the forefront of policy-making in the Canadian North, as both the accelerated effects of global warming and recent demographic trends in the Arctic can threaten the progress made. On the one hand, due to its high fertility rate, the relative population growth in Nunavut from 2011 to 2014 was among the highest in Canada, which exacerbates the housing crisis.[123] At the same time, according to Natan Obed who is the president of Inuit Tapirrit Kantami, “In Inuit Nunangat, our homeland, rising temperatures not only risk undermining our existing infrastructure and increasing food insecurity, it also creates life-and-death situations for even the most experienced hunters [...]”.[124] On average, the North of Canada has warmed by 2.3°C since 1946, i.e. twice as fast as the

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[117] Sheppard, Lola & White, Mason. Many Norths: Spatial Practice in a Polar Territory. Actar. 2017. P 121

[118] Sheppard, Lola & White, Mason. Many Norths: Spatial Practice in a Polar Territory. Actar. 2017. P.122

[119] Ibid, p.123

[120] Ibid.

[121] Ibid, p.124

[122] The Nakasuk School in Iqaluit, Nunavuk (completed in 1974); The legislative Assembly Building of Northwest territories in Yellowknife (completed in 1993); Piqqusilirivvik; the Inuit Cultural Learning Centre in Clyde River, Nunavut (completed in 2011);The East three School in Inuvik (Completed in 2012).

[123] J. Martel, Recent Changes in Demographic Trends in Canada, Statistics Canada, 2015.

[124] N. Obed, How climate change is destroying the Arctic, Macleans’s, June 8, 2019.

Territories/ Regions	Total Population	Aboriginal Identity*			
		First Nations	Métis	Inuit	Other**
NWT	41,786	13,180	3,385	4,075	210
Yukon	35,874	6,685	1,015	230	265
Nunavut	35,944	190	165	30,135	65
Nunavik	13,188	135	30	11,800	20
Nunatsiavut	2,560	25	35	2,290	0
Total	129,352	20,215	4,630	48,530	560

Table 4. Demographic characteristics of the population of Canada's North based on 2016 census. *Statistics Canada. 2017. Northwest Territories [Territory] and Canada [Country] (table). Census Profile. 2016 Census. Statistics Canada Catalogue no. 98-316-X2016001. Ottawa. Released November 29, 2017 (link).*

** According to Statistics Canada, 'Aboriginal identity refers to whether the person identified with the Aboriginal peoples of Canada. This includes those who are First Nations (North American Indian), Métis or Inuk (Inuit) and/or those who are Registered or Treaty Indians (that is, registered under the Indian Act of Canada) and/or those who have membership in a First Nation or Indian band. Aboriginal peoples of Canada are defined in the Constitution Act, 1982, section 35 (2) as including the Indian, Inuit and Métis peoples of Canada. Users should be aware that the estimates associated with this variable are more affected than most by the incomplete enumeration of certain Indian reserves and Indian settlements in the 2016 Census of Population."*
*** These numbers include people with multiple aboriginal responses and aboriginal responses not included elsewhere.*

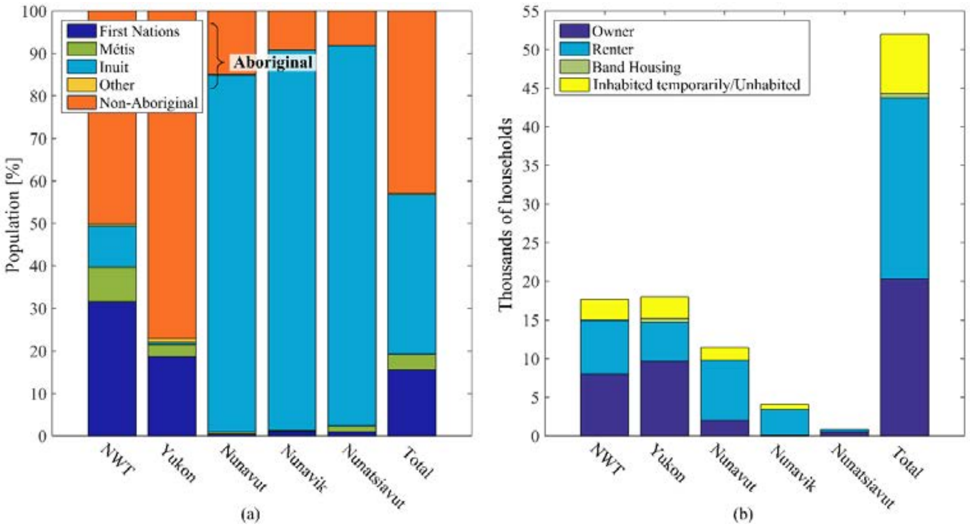

Figure 67. (a) Breakdown of the indigenous and non-indigenous populations and (b) Number of households in each territory and region of Canada's North.

rest of the world[125], affecting the people, ecosystems and infrastructures of the North. This context threatens housing policies and calls for initiatives focusing on quality over quantity. This is why a review of traditional architectural designs of residential dwellings in the North can be so revelatory towards the development of a distinctively Arctic architectural vernacular.

Description of housing building stock in Canada's North

In the present report, "Canada's North" includes the three territories under the jurisdiction of the federal government (Yukon, Northwest Territories (NWT), and Nunavut) as well as two northern regions of provinces belonging to the Inuit area (Nunavik in Québec and Nunatsiavut in Newfoundland-Labrador). Nunavut, Nunavik, Nunatsiavut and Inuvialuit (parts of NWT and Yukon inhabited by Inuit) are referred to as *Inuit Nunangat*. Each region and territory has a distinct legal, historical, demographic and political reality, which has influenced how housing development has taken place.

Before comparing the building stock data of these five regions/territories, it is instructive to have a brief look at their demographic characteristics (see Table 4 [126]and Figure 67.). Indigenous people (Inuit, First Nations and Métis) represent a significant share of the population in each of the five entities. Northwest Territories has the largest population with 41,786 people, 40% of which belong to First Nations, and 11% are Inuit. Yukon's population reaches 38,630 people, and aboriginals are mostly from First Nations (21% of the territory's population). Nunavut has a total population count of 35,944 inhabitants, 83.8% of which being Inuit. Finally, Nunavik and Nunatsiavut have respective populations of 13,188 and 2,560, with a high percentage of Inuit inhabitants. Overall, more than 129 thousand people live in Canada's North as defined above. Table 7 reports the number of households in each territory and region. Note that the last column includes accommodations for temporary workers, as well as abandoned accommodations. The ownership rate in Canada's North is lower than in the rest of Canada, where 68% of households are homeowners according to Canada Mortgage and Housing Corporation, except in Yukon

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[125] Bush, E. and Lemmen, D.S., editors (2019): Canada's Changing Climate Report; Government of Canada, Ottawa, ON. 444 p.

[126] Statistics Canada. 2017. Northwest Territories [Territory] and Canada [Country] (table). Census Profile. 2016 Census. Statistics Canada Catalogue no. 98-316-X2016001. Ottawa. Released November 29, 2017 (link)

Territories/ Regions	Number of households	Owner	Renter	Band Housing	Inhabited Temporarily / Unhabited
NWT	17,666	8,045	6,915	20	2,686
Yukon	17,987	9,680	5,005	530	2,772
Nunavut	11,433	1,960	7,860	-	1,613
Nunavik	4,292	75	3,350	-	667
Nunatsiavut	945	575	255	-	115
Total	52,323	20,335	23,385	550	7,848

Table 5. Number of private accommodations (households) and ownership model within each territory and region of Canada's North, based on 2016 census.
Statistic Canada, Census Profile – 2016 Census, https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E.

Years	NWT	Yukon	Nunavut	Nunavik	Nunatsiavut
–1960	360	1,315	170	20	10
1961–1980	4,805	4,625	2,150	365	160
1981–1990	3,430	2,330	1,995	1,010	150
1991–2000	2,950	2,625	2,095	595	215
2001–2005	1,355	1,045	860	305	115
2006–2010	945	1,435	1,285	575	85
2011–2016	935	1,840	1,260	760	100

Table 6. Number of houses built for a specific period of construction for each territory and region according to 2016 census. *Idem.*

where a similar fraction of owners is found. The smallest ownership rate is in Nunavik, with only a marginal portion of the people owning their house.

The number of houses built over time is shown in Table 6. In all territories and regions, the number of constructions per year peaked in the 1980s, and then decreased significantly. Since mid 2000s, however, the number of houses built per year has started to increase again, and are likely to increase more importantly in a near future. In 2017, the Standing Senate Committee on Aboriginal People released a report denouncing the acute and persistent lack of appropriate and affordable housing in Inuit Nunangat. As recently as 2016, over half of Inuit in Inuit Nunang overcrowded housing.[127] The required number of new housing units, as of 2017, was estimated at 196 for Nunatsiavut, 813 for Nunavik, 3,500 for Nunavut and 144 for Inuvialuit. In its 2019 "Inuit Nunangat Housing Strategy", the federal government called the lack of access to appropriate and affordable housing in Inuit Nunangat a "national crisis".[128] The strategy aims at improving housing outcomes in Inuit Nunangat, building on "direct federal investments [...] and the direct role of Inuit in managing housing in Inuit communities".

The composition of the housing building stock varies from one territorial entity to another. In general, single detached house is the most common housing type in all territories and regions, except in Nunavik where semi-detached housing is more common. A semi-detached house shares one common wall with a neighboring house, as opposed to a single detached house, which shares no common wall with neighbors. Townhouses and small apartment buildings (less than 5 floors) are also relatively common, in particular in Yukon, NWT and Nunavut. Most households in Canada's North are relatively small, having only 4 rooms and less, as revealed by Table 8. Larger households with 8 rooms and more can also be found, mostly in Yukon and Northwest Territories. The state of housing properties is presented for each region and territory in Table 9. A bigger share of household budget is spent in housing in Yukon and NWT. On the other hand, undersized dwellings or those in need of major repair are more frequent in Nunavut, Nunavik and Nunatsiavut.

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[127] https://www.rcaanc-cirnac.gc.ca/eng/1554820296529/1554820324561 (Annex 3)

[128] https://www.rcaanc-cirnac.gc.ca/eng/1554820296529/1554820324561 (Introduction)

Territories	**Nunavik**	**Nunavut**	**Nunatsiavut**	**Yukon**	**NWT**
Type of household	**Number of households**				
Single detached	1,230	4,370	770	9,495	8,685
Semi-detached	1,730	875	35	1,160	975
Townhouse	150	2,960	25	950	1,595
Duplex	60	175	0	605	385
Apartment with less than 5 floors	450	1,300	0	1,770	2,375
Apartment with 5 floors and more	0	110	0	50	450
Mobile housing	0	20	5	1,185	505
Other household	2,395	5,335	0	4,550	5,400

Table 7. Number of households for each housing type for each territory according to 2016. *Statistic Canada, Census Profile – 2016 Census, https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E*

Territories and regions	**Nunavik**	**Nunavut**	**Nunatsiavut**	**Yukon**	**NWT**
Number of rooms	**Number of households**				
1 to 4	2,100	4,865	235	5,160	5,350
5	785	2,515	310	2,675	3,235
6	440	1,435	160	2,340	2,480
7	240	625	75	1,755	1,600
8 or more	70	380	55	3,285	2,310

Table 8. Number of households for different number of rooms for each territory according to 2016 census. *Idem.*

	Rental house		**Ownership house**		**Total of property**	
Territories	**Spending 30% or more of income on shelter cost**	**In subsidized housing**	**Spending 30% or more of income on housing**	**With mortgage**	**Major repairs needed**	**Undersized dwellings**
Nunavik	3.2%	86.3%	0.0%	31.2%	20.4%	31%
Nunavut	5.2%	83.5%	7.9%	60.2%	26.1%	31%
Nunatsiavut	7.7%	25%	5.2%	41.7%	28.7%	10.8%
Yukon	29.4%	25.1%	12.7%	59.9%	12.5%	4.8%
NWT	16.3%	41.3%	9%	61.1%	18.1%	10.5%

Table 9. State of housing properties for each territory. *Idem.*

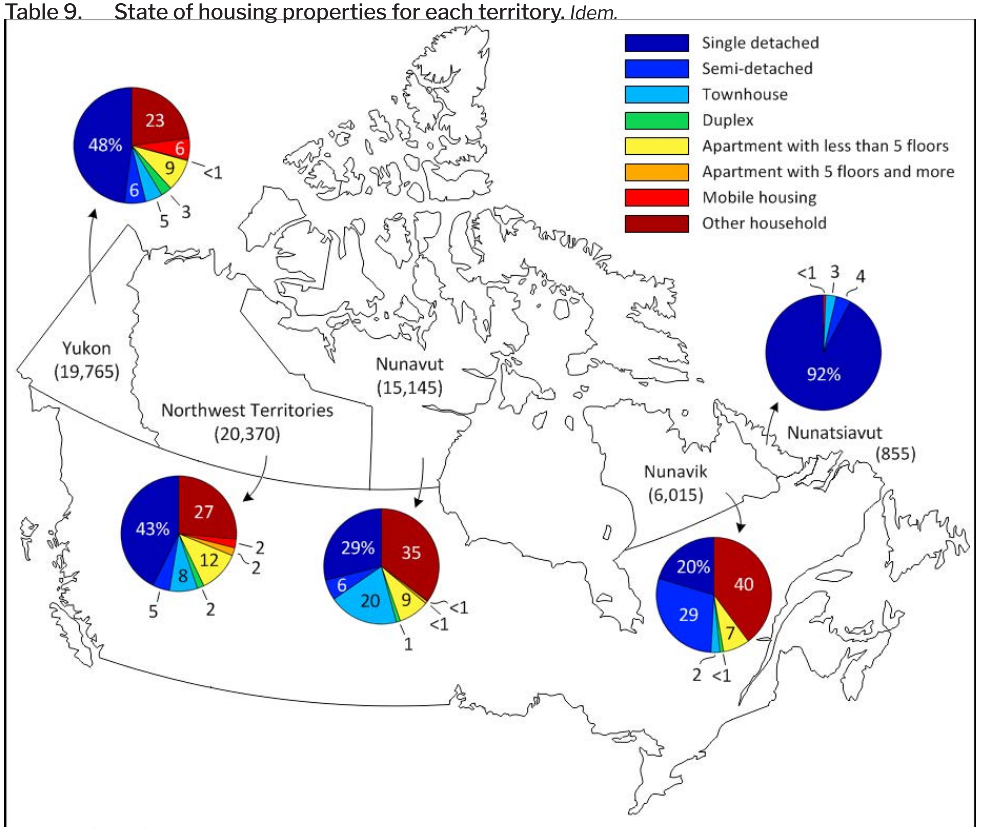

Figure 68. Share of different housing types in the different territories and regions.

Typical building design and energy consumption

This section presents a summary of the main features of housing designs in the North. Recommended practices are highlighted. Examples of buildings that have been documented in open literature are presented.

The Société d'habitation du Québec has established good design practice guidelines[129] for the construction of houses in Nunavik. Special care must be taken to avoid permafrost thawing, which could jeopardize the integrity of the building. As a result, buildings are usually jacked 0.6 to 1.2 m above the ground level to minimize heat transfer to the ground. The aerodynamic properties of the building shape are important, to sustain the potentially high wind load and to control snow accumulation. A relatively flat roof is used so that strong wind can remove snow accumulation. A small envelope surface is desired to minimize heat losses, with a minimal insulation of RSI 5.11. The details of the envelope design are extremely important to ensure air tightness (membranes) and prevent moisture transfer in cold parts of the envelope where it could condense. A maximal window-to-wall ratio of 30% and a U-value smaller than 2.0 to 2.5 W/m^2K are recommended. As will be explained below, houses are heated by fuel oil. A technical room gathers all the pieces of equipment (furnace, tanks, etc.). Water tanks are needed and must be in a heated room, as in most villages water is delivered by trucks (wastewater is also collected that way). The layout of the dwelling and the furniture must be adapted the Inuit lifestyle. The typical annual heating demand is 310 kWh/m^2. An example of buildings that was designed in collaboration with Inuit and that achieves a higher energy performance is detailed in Chapter 4.

The Department of Public Works and Services of the government of the Northwest Territories has also published a report on good building practices for northern facilities.[130] Careful design and construction are required to ensure water resistant building envelope with low air leakage because of the cold and dry climate. Acceptable values for air leakage depend on the indoor air humidity of the buildings as it is not recommended to have very dry indoor environment. The maximum recommended air leakage rate values is 0.15 L/s per square meter of floor area @75 Pa for all buildings with low indoor air humidity (below 27%), 0.1 L/m^2s for buildings with normal humidity level (27 to 55%) and 0.05 L/m^2s for buildings with high indoor humidity (more than 55%). Air and vapour barriers are thus necessary and should be located on the exterior of structural framing. The minimum thermal resistance of opaque envelope is RSI 7.0 for suspended floors, RSI 3.5 for floors on non-frost susceptible soil, RSI 5.6 for walls and RSI 8.75 for roofs. There is no prescribed value for floors installed above thermosiphon grids. A minimum drainage slope of 4% is preferable for roofs. All windows are recommended to have as a minimum double-glazed sealed glazing units with low-e coating or to have triple-glazed sealed units. Use of tinted glass with shading coefficients greater than 10% is not recommended since it limits potential for passive solar gains. As for the mechanical equipment, less than 25% of all communities in the Northwest Territories have piped service for domestic water. For the unpiped communities, water is delivered by truck and stored in holding tanks located within buildings as in Nunavik. Deliveries are generally made once or twice a week. The clean water tank must be kept between 5 and 15°C and should not be located in the same room as boilers or furnaces as warm water can support bacteria. If the tank is too large to fit within the occupied building areas, a heated crawl space should be installed to place the water tank. For hot water, oil-fired heaters are preferred for smaller buildings and indirect-fired heaters for larger buildings. Burner efficiency above 80% is suggested. Designers are encouraged to consider more energy-efficient ventilation strategies that meet the requirements of ASHAE 62.

A highly energy-efficient house was designed and built by the Northwest Territories Housing Corporation (NWTHC) in Inuvik, NWT[131] Figure 69. A design charrette was help with local stakeholders and revealed specific interests such as the reduction of the environmental impact. The duplex has a total surface area of 247 m^2, and integrated solar thermal hot water system in addition of 3.6 kW photovoltaic (PV) panels. The excess electricity produced by the PV, if any, is fed to the grid. According to preconstruction models, each dwelling is expected to consume annually 7,040 kWh of electricity (59 kWh/m^2) and 46 GJ of natural gas (0.38 GJ/m^2 or 107.4 kWh/m^2).

The government of Nunavut issued a guide for good building practice design[132]. For the envelope, minimal RSI values of 4.9 for walls and 7.0 for roofs are demanded. For windows, insulated frame PVC, vinyl or pultruded fibre reinforced plastic frames are preferred, with low-E double-glazing. Wood and prefabricated steel frame buildings are common in Nunavut. Wood is seen as

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[129] http://www.habitation.gouv.qc.ca/fileadmin/internet/publications/0000024197.pdf

[130] Government of the Northwest Territories, Good building practice for northern facilities, 2013.

[131] https://assets.cmhc-schl.gc.ca/sf/project/cmhc/pubsandreports/pdf/68120.pdf?rev=4f3a51f4-39c1-4c05-aa10-b4de13b66426

[132] Government of Nunavut, Good Building Practice Guideline, Second Edition, 2005.

Figure 69. High energy performance house built in Inuvik (NWT).
https://assets.cmhc-schl.gc.ca/sf/project/cmhc/pubsandreports/pdf/68120.pdf?rev=4f3a51f4-39c1-4c05-aa10-b4de13b66426

Figure 70. Arviat E/2 Northern Sustainable House (Nunavut).
https://www.cmhc-schl.gc.ca/en/data-and-research/publications-and-reports/arviat-e-2-northern-sustainable-house-energy-consumption-performance-assessment

versatile, compact, easily available and not susceptible to damage during transport. Less than 20% of all communities in Nunavut have piped service. In that case, water is delivered by trucks and must be stored in tanks. District heating might be available in some places, but a backup heater is usually needed. The set point temperature is 21°C in winter and 24°C in summer. Forced hot air or hydronic heating systems are both used. As few buildings in Nunavut have basements, counter-flow furnaces are generally required with ducts located in a raised floor. Lighting is mentioned as an important electric load to consider (30% of electrical load).

The Arviat E/2 Northern Sustainable House shown in Figure 70 was designed and built by Nunavut Housing Corporation, with the involvement of the Canada Mortgage and Housing Corporation (CMHC). The objective was to use 50% less energy compared a comparable house that would been designed and build according to the 1997 Model National Energy Code for Houses (MNECH). The house has a heated surface area of 128 m^2 and different strategies and technologies were used to cut down the energy demand. The energy bills indicated an annual consumption of electricity of 29 GJ and of oil of 218 GJ, representing energy intensity of 62.9 kWh/m^2 for electricity and 473.1 kWh/m^2 for oil. This was only 14% less than the reference building, likely due to the number of occupants that was larger than that initially assumed, the presence of a sewage tank outside the house that needed to be heated (which was not initially planned) and differences in weather conditions. According to CMHC, “this project demonstrated that energy-efficient and culturally appropriate houses can be delivered in Canada’s North”, but also that “achieving targeted design performance not only involves good design and best construction practices, [but] also involves understanding and planning for post-occupancy operation of the house”.

In Yukon, no governmental organization has issued a guide for good building practice designs. However, in the 2019 version of its strategy for climate change, energy and a green economy, Yukon sets the target of supplying 40% of its heating needs by renewable energy sources in 2030.[133] The government expects in the next decade a reduction of 21 kilotonnes of carbon emissions by making buildings more energy efficient, 9 kilotonnes by introducing electric heat pumps and 8 kilotonnes by installing renewable heating systems in governmental buildings. The government of Yukon will invest $30M per year for the

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[133] Government of Yukon. Our Clean Future: A Yukon strategy for climate change, energy and a green economy. 2019. https://yukon.ca/en/draft-our-clean-future

next decade to reach this objective. A financial program has been developed to help homeowners to retrofit their home to improve its energy performance. Rebates are also possible to switch to renewable energy for heating or to install photovoltaic solar panels on the roof. The need to design buildings so they become more resilient to fires, floods, permafrost thaw and heat stress is mentioned. The need for a building standards manual for the design and construction of new buildings is also acknowledged by the strategy for climate change guide.

Bylaw 99-50 in Whitehorse, the capital city of Yukon, asks for minimal insulation level of RSI 4.9 for walls (including foundations above and below grade) and floor above unheated spaces, RSI 8.8 for ceilings, RSI 1.8 for slabs on ground (but RSI 3.5 for slabs on ground containing radiant heat) and RSI 1.8 for crawl space from grade.[134] Doors need to have a minimum thermal resistance of RSI 2.1 and windows should have at least RSI 0.625. In terms of airtightness, the building envelope of new dwellings must be constructed with a maximum of 1.5 air changes per hour at a 50 Pa depressurization. Heat recovery ventilators with a sensible recovery efficiency of 64% or more are mandatory.

Two houses located in Dawson City, Yukon, were built in 2008 and 2009.[135] One of them, the Dawson E/8 house, has been designed with passive solar features and a solar hot water system, with 11 m^2 collectors on the porch roof. It is estimated that the annual total radiation available on the collector is 39 MJ. Studies showed that increasing the surface of the roof, and changing slope and orientation would significantly increase the amount of energy available.

Energy supply of the North

In Nunavut, Qulliq Energy Corporation is a state-owned company mandated to provide electricity to the inhabitants of Nunavut. It operates 25 diesel power plants with a total installed power around 76 MW[136] and an annual energy consumption of 184 GWh.[137] A pilot project integrated 3 kW of solar panels to the grid in Iqaluit in 2016. It was the first time that a renewable energy source connected to any grid in Nunavut. Kugluktuk is now planning to integrate 500 kW of photovoltaic panels to its diesel power plant.[138] A study of 2016 analyzed the potential of wind turbines for electricity generation.[139] The analysis revealed that in 8 of the 25 communities of Nunavut, the return on equity on wind projects was close or above 8%, which was considered appropriate in today's market. Qulliq currently has a program allowing customers to produce their own electricity from renewable sources (up to 10 kW) and to integrate it to the grid.

Northwest Territories counts two utilities, namely the Northwest Territories Power Corporation (NTPC), a crown-owned public utility, and Northland Utilities, an investor owned electricity utility.[140] The total installed capacity is around 269 MW[141] and the annual consumption, 624 GWh. This includes utilities and production by industries (e.g., mines). Among the 33 communities of NWT, none is connected to the main North American grid, and many are isolated and supplied by diesel power plants. As a result, most of the installed power relies on fossil fuels (68% from diesel, and 8% from natural gas). Nevertheless, NWT has three hydroelectricity facilities totaling 20% of the installed capacity. Wind turbines and a small fraction of PV electricity production account for the remaining capacity (less than 4%). It is interesting to note that 40% of electricity consumed is actually hydroelectricity. The capacity of the thermal power plants is relatively high in order to cover for low water years.

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[134] City of Whitehorse. Building and Plumbing Bylaw. https://www.whitehorse.ca/departments/planning-building-services/building-inspections

[135] http://publications.gc.ca/collections/collection_2015/schl-cmhc/nh18-22/NH18-22–115–1-eng.pdf

[136] https://www.qec.nu.ca/

[137] https://www.nrcan.gc.ca/our-natural-resources/electricity-infrastructure/electricity-canada/canadas-electric-reliability-fra/nunavuts-electric-reliability-framework/18840

[138] https://www.nrcan.gc.ca/our-natural-resources/electricity-infrastructure/electricity-canada/canadas-electric-reliability-fra/northwest-territories-electric-reliability-framework/18838

[139] https://nunavutnews.com/nunavut-news/kugluktuk-power-plant-featuring-500-kilowatt-solar-capacity-gets-funding/ http://www.qec.nu.ca/sites/default/files/potential_for_wind_energy_in_nunavut_communities_2016_report_0.pdf

[140] https://www.nrcan.gc.ca/our-natural-resources/electricity-infrastructure/electricity-canada/canadas-electric-reliability-fra/northwest-territories-electric-reliability-framework/18838

[141] https://www.inf.gov.nt.ca/sites/inf/files/resources/electrical_generation_in_the_nwt_4_converted.pdf

Figure 71. Solar panels in Kuujjuaq, Québec.
Makivik Organization (www.makivik.org).

Type of electricity production	Nunavut* (2017)	Yukon** (2014)	NWT*** (2015)	Nunavik (2012)****	Nunatsiavut (2013)
Solar	-	148.1	807	-	-
Hydaulic turbine	-	95,303	53,800	-	-
Wind turbine	-	740.5	9,146	-	-
Combustion by diesel	78,415	44,430	182, 920	30,400	8,500
Combustion by natural gas	-	8,886	21,520	-	-
Total	78,415	148,100	269,000	30,400	8,500

** Statistique Canada. (Tableau 25-10-0022-01). Centrales installée, puissance génératrice annuelle selon le type de production d'électricité, https://doi.org/10.25318/2510002201-fra*
***Natural Resources Canada. Canada's electricity supply generation mix varies significantly among Canada's provinces and territories. https://www.nrcan.gc.ca/our-natural-resources/energy-sources-distribution/electricity-infrastructure/electricity-canada/canada-electric-reliability-framework/18792*
**** Natural Resources Canada. Canada's electricity supply generation mix varies significantly among Canada's provinces and territories. https://www.nrcan.gc.ca/our-natural-resources/energy-sources-distribution/electricity-infrastructure/electricity-canada/canada-electric-reliability-framework/18792*
***** Plan d'approvisionnement 2014-2023 des réseaux autonomes, Hydro-Québec Distribution, Demande R-3864-2013 (link) – Only the power capacity of the villages is included.*

Table 10. Electrical power capacity [kW] by type of production for each territory and region.

The installed capacity (utility and industry) in Yukon is 131 MW and the annual electricity consumption, around 417 GWh.[142] Yukon Energy Corporation (YEC) is a Crown corporation and the main generator and distributor of electricity. ATCO Electric Yukon is a privately owned company purchasing power from YEC and generating electricity as well. The transmission and distribution system consists of six isolated power grids, five of which service small areas. Most of the power is already from renewable sources. In 2013, Yukon Energy generated 99.5% of its electricity via hydroelectric dams and wind turbines,[143] with thermal power plants covering for periods of high electricity demand and low water levels. As a result, electricity in Yukon is much cheaper than in NWT or Nunavut. A representative price for electricity in 2016 in NWT and Nunavut was above 0.30$/kWh, and 0.136$/kWh in Yukon (the average price in Canada was 0.129$/kWh).[144]

In Nunavik, the 14 villages are not connected to the main power grid due to their remote locations. Therefore, diesel power plants provide electricity to each community. The plants are managed by Hydro-Québec, the state-owned public utility in the Province of Québec for the generation, transmission and distribution of electricity. As of 2012, the peak demand for the villages in Nunavik was 15.46 MW and the installed capacity, 30.04 MW.[145] The smallest diesel power plant was in Aupaluk (0.78 MW) and the largest, in Kuujjuaq (6.25 MW). Nunavik's annual need in electricity is 82.4 GWh for the communities,

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[142] https://www.nrcan.gc.ca/our-natural-resources/electricity-infrastructure/electricity-canada/canadas-electric-reliability-fra/yukons-electric-reliability-framework/18800

[143] https://www.cbc.ca/news/canada/north/yukon-n-w-t-and-nunavut-differ-in-outlooks-for-renewable-energy–1.2804345

[144] https://www.cer-rec.gc.ca/nrg/ntgrtd/mrkt/snpsht/2017/02-03hghcstpwr-eng.html?=undefined&wbdisable=true

[145] Plan d'approvisionnement 2014-2023 des réseaux autonomes, Hydro-Québec Distribution, Demande R-3864-2013 (link).

representing more than 24 million liters of diesel and 65,000 tons of CO_2,eq.[146] As of today, the electricity supply of Nunavik relies almost exclusively on diesel. In order to reduce greenhouse gases emissions, different projects promoting renewable energy sources have emerged recently. For example, the Innavik Project (scheduled for 2022) is a 7.5 MW run-of-river hydroelectric facility to replace reliance on diesel fuel for almost all of the energy need of the village of Inukjuak.[147] Other examples include the installation of 70 kW of photovoltaic panels on buildings in the village of Kuujjuaq.[148] The use of photovoltaic panels is also experimented in the village of Quaqtaq.[149]

The energy supply in Nunatsiavut is similar to that of Nunavik and Nunavut. The five villages constituting Nunatsiavut are also off-grid and served by isolated diesel power plants. The total installed electric power for all these communities is around 8.5 MW[150].

Due to the low fuel-to-electricity conversion efficiency of diesel power plants, electricity is not used for heating purposes in regions served by diesel power plants. In place, buildings are equipped with fuel oil heating systems. In some communities, centralized heating systems relying on the recovery of waste heat from the diesel power plants can sell thermal energy for space heating and domestic hot water heating. Commercial scale centralized heating systems are already in place in Iqaluit, Rankin Inlet, Arviat and Kugluktuk. According to Qulliq, without the centralized heating systems, an additional 3 million liters of oil would be required every year. Table 10 summarizes the electrical power capacity by type of production for each territory and region. For Nunavik and Nunatsiavut, the values only account for installed power from utility, whereas for Nunavut, Northwest Territories and Yukon, the values consider both utility and industrial installations.

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[146] S. Hendrie, Solar power works better in Kuujjuaq than Los Angeles, Taqralik, Winter 2020.

[147] https://www.innavikhydro.com/

[148] S. Hendrie, Solar power works better in Kuujjuaq than Los Angeles, Taqralik, Winter 2020.

[149] http://voirvert.ca/nouvelles/rubriques/hydro-quebec-ere-energie-solaire-photovoltaique

[150] https://nlhydro.com

Japan

Housing History in Hokkaido after Japanese Restoration

Before the end of Edo era, about 200 years ago, the indigenous people Ainu lived in their typical house, *Cise* or *Chise*. During the Japanese invasion through the end of Edo era and Meiji restoration, the number of Ainu people has been rapidly decreasing. The knowledge of building the cise was almost lost. But the houses were said to be warmer than Japanese houses. Figure 72 shows the Japanese style house built in 1875. The house used a Japanese traditional post and beam system as a construction method. Both sides of the posts are covered with wooden siding. The space between wooden siding was usually vacant. The heating system was usually hearth. It generated smoke and a poor indoor air quality.

After World War II, the Japanese government instituted an act on cold-proof housing in Hokkaido. After the act, the Hokkaido prefectural cold region housing research institute was established. Also, the departments for building techniques were established in the universities in Hokkaido. The research communities were composed of local government officials, the research institute, the universities, and builders who have been implementing research and development. Figure 74 shows the first type of mass supply housing in the 1960s in Hokkaido. They used concrete blocks to avoid fires which were the

Figure 72. Tonden-heisha in Kotoni, Sapporo.

Figure 73. Tonden-heisha herth

Figure 74. Mass supply houses developed in the 1960s.
Endo Akihisa,1994,Hokkaido Jyuutakushiwa, Vol.2, Sumaino Tosyokan Syuppankyoku.

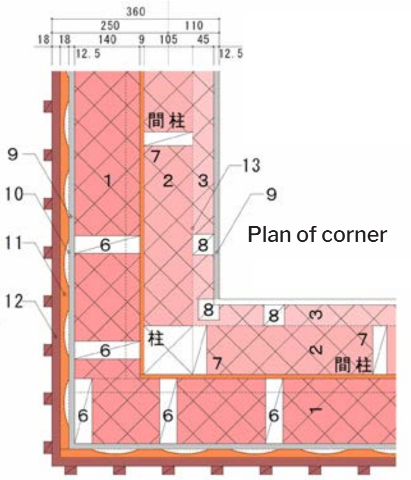
Figure 75. Housing type 1970–1980.

most serious problem at that period. People who wanted to use public loans needed to build this type. This housing type was sufficiently airtight. But since it did not have enough insulation, RW, 30 mm was installed on the ceiling, causing a huge moisture problem.

In the early 1970's, the main energy source in Hokkaido changed from coal to oil. After that, the oil shock happened. People became aware that energy efficient homes were essential. Also, during 1970–1980, the population in Hokkaido was rapidly increasing. Especially in Sapporo city, the capital of Hokkaido, the building area for a house became smaller and smaller. Therefore, the newly constructed houses needed to carry snow loads during winter. The research communities developed the house shown in Figure 75. The construction method of those houses was a Japanese traditional post and beam system. The spaces between posts were filled with glass wool. For windows they used a double sash with single pane glass. The housing type was called the first insulated mass supply Japanese house. But the builders were not concerned about the airtightness of the building type, thus resulting in serious deterioration.

Through the research and development for housing type, Hokkaido local government launched the Northern Housing Project in 1989. In this project, the recommendations for energy efficiency and air-tightness were determined for the first time in Japan. The techniques were imported from northern Europe and Canada through a research and development project and modified to fit the Japanese traditional construction. Recently, the research community has been improving the energy efficiency of detached houses under the project. Figure 76 shows the system of energy efficiency for a traditional Japanese wooden frame.

Hokkaido local government made the semi-public housing data stock system



1. GW (glass wool) 140mm
2. GW105mm
3. GW50mm
4. GW235mm
5. EPS150mm
6. 38×140
7. 30×105
8. 45×45
9. PB12.5mm
10. Wind protection layer
11. Furring strips
12. Exterior
13. Vapour protection layer
14. Sealer

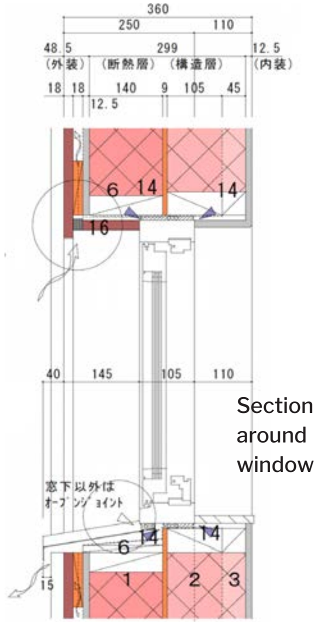
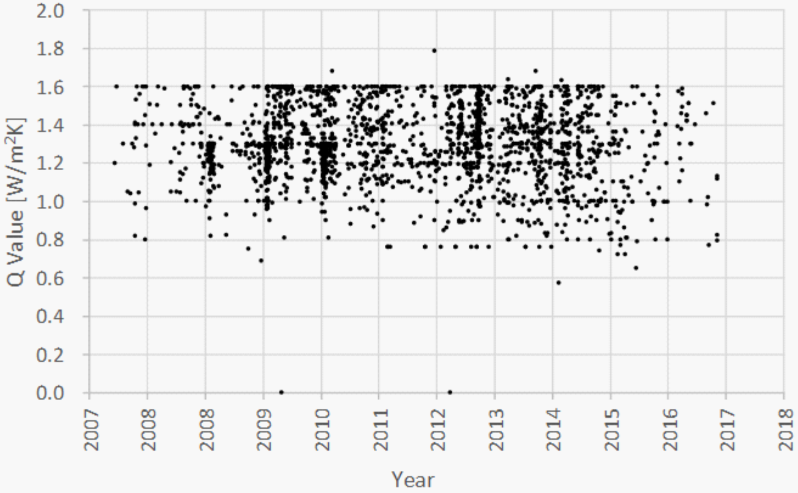
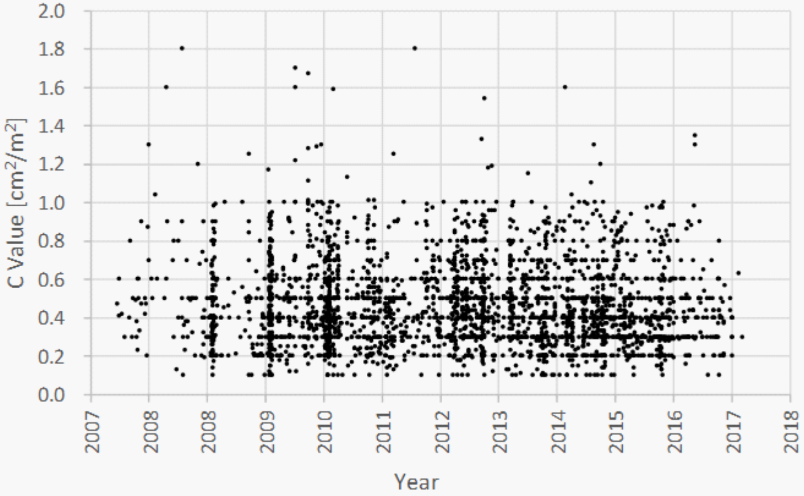


Figure 76. Insulation and air-tightness system for traditional Japanese wood frame.



Overall heat-loss coefficient (include ventilation loss)



Air-tightness area

Figure 77. Energy efficiency of a recent detached house in Hokkaido.

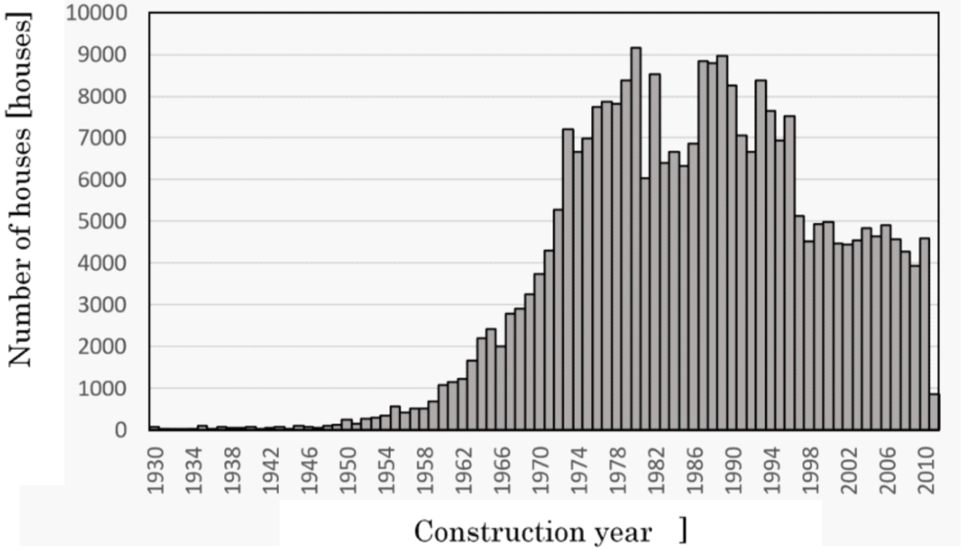


Figure 78. The construction years of existing housing stock in Sapporo city.

under the Northern Housing Project in 2007. The government recommends storing housing data for future renovation and circulation purposes.

Figure 77 shows the overall heat-loss coefficient (OHC) and the air-tightness area (ATA) uploaded to the data stock system. OHC should be under 1.6 to be Northern Housing. Also, ATA should be under 2.0. Recently, almost all houses are under 1.6 and 1.0, respectively under the effort of R&D project. Figure 78 shows the housing stock in Sapporo city. The energy efficiency of the recent housing stock has been improved. But the main housing stock in Hokkaido dates from 1975–1980 and 1985–1990. Houses built in that era have issues with energy efficiency and with moisture. Also, the Japanese population is already decreasing. Then R&D for renovation with energy efficiency is essential.

GHG emissions in the current building stock of Hokkaido

In recent years, in the field of construction in Japan, construction with energy efficiency has been promoted to combat global warming. Housing companies have attempted many trials toward ZEH (Zero Energy Housing) with passive technologies and renewable energies.

The Japanese government has several targets for ZEH. In the 5th National Energy Plan, "in more than half of the detached houses newly built by 2020 and in the average of newly built houses by 2030, the houses should be ZEH".[151]

In the National Countermeasures Plan against Global Warming in May 2016, "Japanese government aim that more than half of newly built detached houses constructed by the top makers will be ZEH by 2020."[152] In the Future Investment Strategy in 2017, "Japanese government aims that newly constructed houses and the non-residential buildings will be ZEH and ZEB (Zero Energy Building) by 2030"[153]

Local builders without enough knowledge about energy efficiency and design-centered architects are opposed to this. As mentioned above, Hokkaido has been implementing long-term efforts on the energy efficiency of houses, making Hokkaido an advanced area about housing energy efficiency in Japan. However, the climate is colder than other areas in Japan and there is much snow, so housing consumes more energy in Hokkaido than in other areas. ZEH in Hokkaido also has some difficulties. It is challenging to install renewable energies such as PV because of high latitude and high snowfall. Therefore, in this section, we examined the approach to zero carbon in current energy-efficient houses.

Wood Construction in Hokkaido

Japan is one of the forest countries of the world. However, the country's forestry has been declining for a long time because it has lost price competition. In recent years, Japanese people have understood that it is necessary to use domestic timber to grow forests and forests are important for tackling the global environmental problem and disaster prevention. Then, Japanese timber is gradually getting more popular. Hokkaido has forests equivalent to about 1/4 of the domestic forest area. The planted forest resources, mainly larch and fir, are maturing. Their resource value and availability are increasing. The self-sufficiency rate of wood in Hokkaido has exceeded 50% since 2006, but unfortunately, it is mainly used for industrial materials and pulp. The percentages for the usage of building material is not so high. The characteristics of forest trees in Hokkaido, the cold and snowy climate, and the dry indoor environment etc. are the reason not to increase the percentage. In this section, we report the use of artificial forest timber in Hokkaido and the current status and issues of the timber industry.

Hokkaido has 5.54 million hectares of forests, of which 1.5 million hectares are planted, accounting for 14.5% of the country. The supply of Hokkaido timber (3.55 million m^3) accounts for 17.0% of the domestic timber supply (19.65 million m^3)[154]. The forest resources in Hokkaido play an important role in the domestic timber industry.

Sakhalin fir and Japanese larch occupy 52% and 29% of the total area of planted forests in Hokkaido, respectively. Both tree species are the representative forestation species. From the 1950s and 1970s, afforestation was actively carried out in Hokkaido in the 1950s and 1970s. The peak of forest age is 36–45 years old for Sakhalin fir and 41–50 years old for Japanese larch.[155] The total stock of planted forests has increased from 187 million cubic meters in 2001 to 247 million cubic meters in 2013 as shown in Figure 79, and the size of the lumber is large enough to provide building materials.

Under these resource conditions, looking at the supply and demand of timber in Hokkaido,[156] the self-sufficiency rate for demand (6,980,000 m^3) is 55.6%, twice the national self-sufficiency rate (27.9%). However, this is largely due to the high self-sufficiency rate of pulp (48%), which accounts for half of the demand in Hokkaido. Figure 77 shows the use of artificial forest timber (3.13 million m^3), which accounts for

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[151] Outline of Energy White Paper 2019, https://www.meti.go.jp/english/press/2019/0607_001.html

[152] The Basic Environment Plan,Cabinet decision on April 17, 2018,http://www.env.go.jp/policy/kihon_keikaku/plan/plan_5/attach/ref_en-01.pdf

[153] Growth Strategy 2018(Detailed measures), https://www.kantei.go.jp/jp/singi/keizaisaisei/pdf/miraitousi2018_en2.pdf

[154] Ohashi Yoshinori, Use of Artificial Forest Wood in Hokkaido and Trends in Building Material Development,in Japanese, Mokuzai Kogyo,Vol. 69, No. 10, 2014

[155] Ohashi Yoshinori, Use of Artificial Forest Wood in Hokkaido and Trends in Building Material Development

[156] Hokkaido Forestry Statistics 2013,Hokkaido Government Forestry Bureau

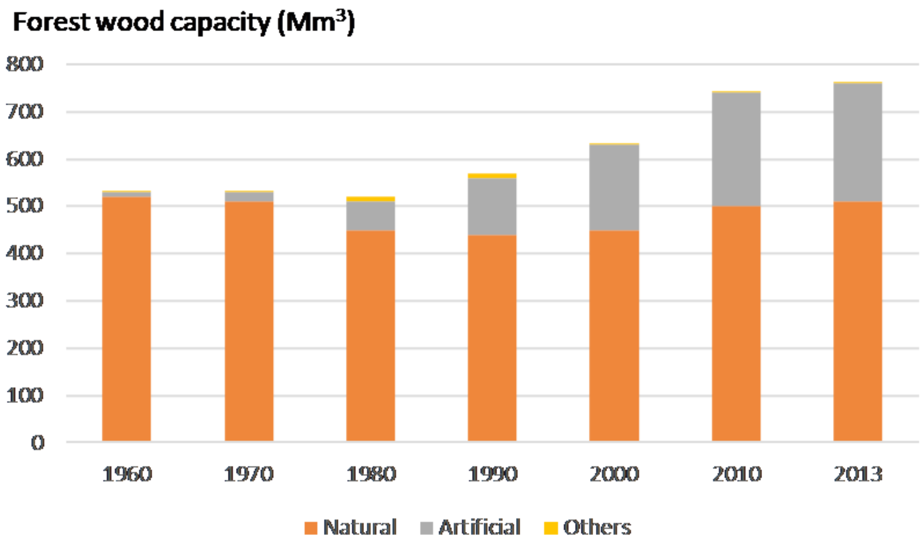

Figure 79. GIS data for urban development in Hokkaido, Change of forest capacity in Hokkaido.

81% of the timber supply (3.88 million m³). Approximately half of the sawmill in Sakhalin fir are used for construction, but 58% of them are low-priced materials such as base materials and boards. There are only a few applications such as cedar pillars in Honshu. In Japanese larch, packing and pallets account for 82% of sawmills. Only 2% is used for construction, and 16% is small, including the lamina base plate for laminated wood.

As mentioned above, although the self-sufficiency rate of the use of the Hokkaido forest is over 50%, low-value applications such as industrial materials and pulp are mainly used. For sustainable forestry management, stable supply of artificial forest timber, and promotion of the timber industry, it is important to expand applications with high-value and improve processing techniques in the region.

Hokkaido, a cold region, requires an indoor environment that heats the entire building during the winter season. At that time, the room tends to dry out, and the relative humidity drops to 30%. In such an environment, the moisture content of wood is 7 to 8%. It is problematic to use wood and wood materials. In particular, in the case of Japanese larch, when wood with high moisture content is used, the woods tend to shrink and deform, and cracks and gaps in the finished material, floor noise and

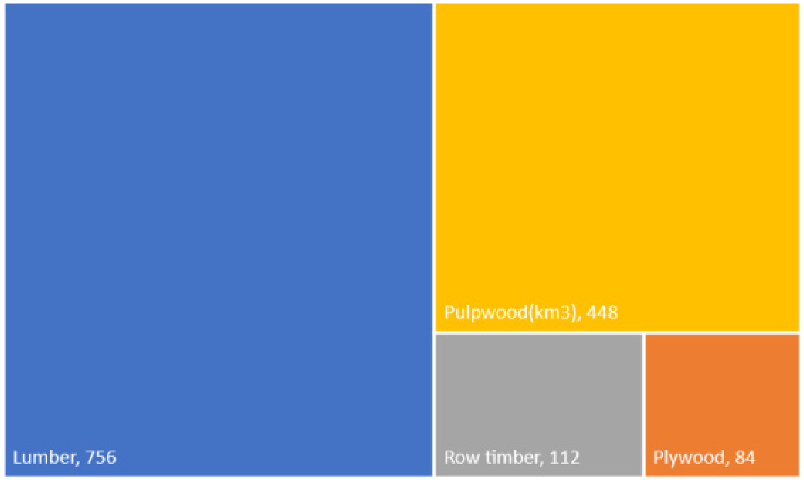

Figure 80. Usage of Sakhalin fir, from artificial forest in Hokkaido.

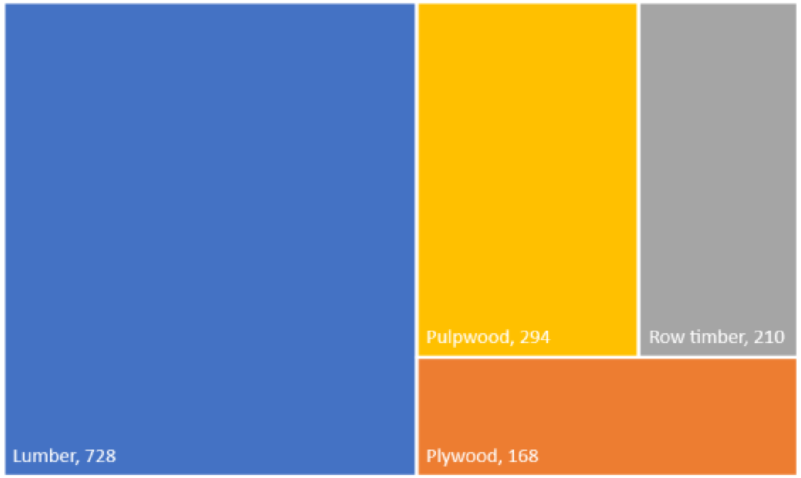

Figure 81. Usage of Japanese Larch, from artificial forest in Hokkaido.

fittings are likely to occur.

Therefore, the Hokkaido Forest Products Research Institute has developed a product called “Core Dry”.[157] First, the timber is collected from the logs, and then the inside is sufficiently dried while suppressing surface and internal cracks by the developed drying process. Japanese larch is a material that tends to be twisted, but this product achieves dimensional stability equal to or better than laminated wood even in a dry environment in a winter room by setting the moisture content of the entire cross section to less than 11%.

In Japan, the application of wooden buildings to large buildings has not been promoted due to the strict regulations on fire prevention, but the use of large buildings has begun to progress gradually with the government and the response to environmental issues. Figure 83 (bottom) shows the CLT test building using Sakhalin fir and Japanese larch at the Hokkaido Forest Products Research Institute. CLT is expected worldwide as a wooden building material for large buildings. It was confirmed that CLT could be made using two major forest species in Hokkaido. Figure 83 (above) shows a wooden barn. Barns have often been made of steel, but the use of a wooden structure has improved the insulation and freezing accidents. In addition, the maintenance of rust was reduced. Hokkaido is also Japan’s most agriculturally active area. It is necessary to promote wooden construction for such production facilities.

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[157] Core Dry, Hokkaido Forest Products Research Institute,2013

Figure 82. Core dry.

Figure 83. Wood construction in Hokkaido.
Design proposal of Wooden barn, Hokkaido Government Forestry Bureau.

5. CASE STUDIES

(Finland, Canada and Japan)

Finland

Wood is the only construction material in the Arctic with which carbon neutrality is possible to achieve (and traditional resource-wise solutions should be considered when designing new structures)

Introduction

The designs of the two case-study buildings are based on issues of consideration chosen of the relevant characteristics of zero-carbon building and traditional architecture. The case-study buildings, described in the following chapter, are based on the guidelines of this chapter, together with the general issues of consideration for building in the Arctic.

The research aims at the development of the assessment method for assessing greenhouse gas (GHG) emissions from building in the Arctic districts and analysis of GHG impacts of Arctic buildings. From the viewpoint of carbon neutrality, several issues may affect the options and possibilities of carbon neutrality and the issues that are considered in the assessment method:

- Because of cold climate, there is a need for good structural energy-efficiency. Extra insulation and other structural solutions increase the share of embodied GHGs.

- Timber is a much used building material in some Arctic districts.

- The share of small houses of the overall residential building stock is typically bigger than the average in the country.

- Because of climatic and geographical reasons, it is often difficult to supply renewable energy through the year. This applies especially for solar energy, and in many Arctic districts also for geothermal energy though there are exceptions for this.

- Wind energy may be a potential solution for renewable energy supply, but this has to be considered with sensitivity from the approach of Sámi livelihood and traditional landscape

- Solar energy is possible in the summer season.

- To achieve annually net zero GHGs, seasonal surplus renewable energy is often needed.

- District scale approaches may be beneficial or needed to find best solutions for renewable energy supply.

- Energy storages and heat pumps may be needed.

- Carbon storage in timber may be an issue to be considered in LCA principles

- Time scale of assessment may be an important issue to be considered in LCA principles.

- The impact of transportation and construction / maintenance / demolition works may differ from “conventional” LCA studies because of long distances, limited infrastructure and harsh weather.

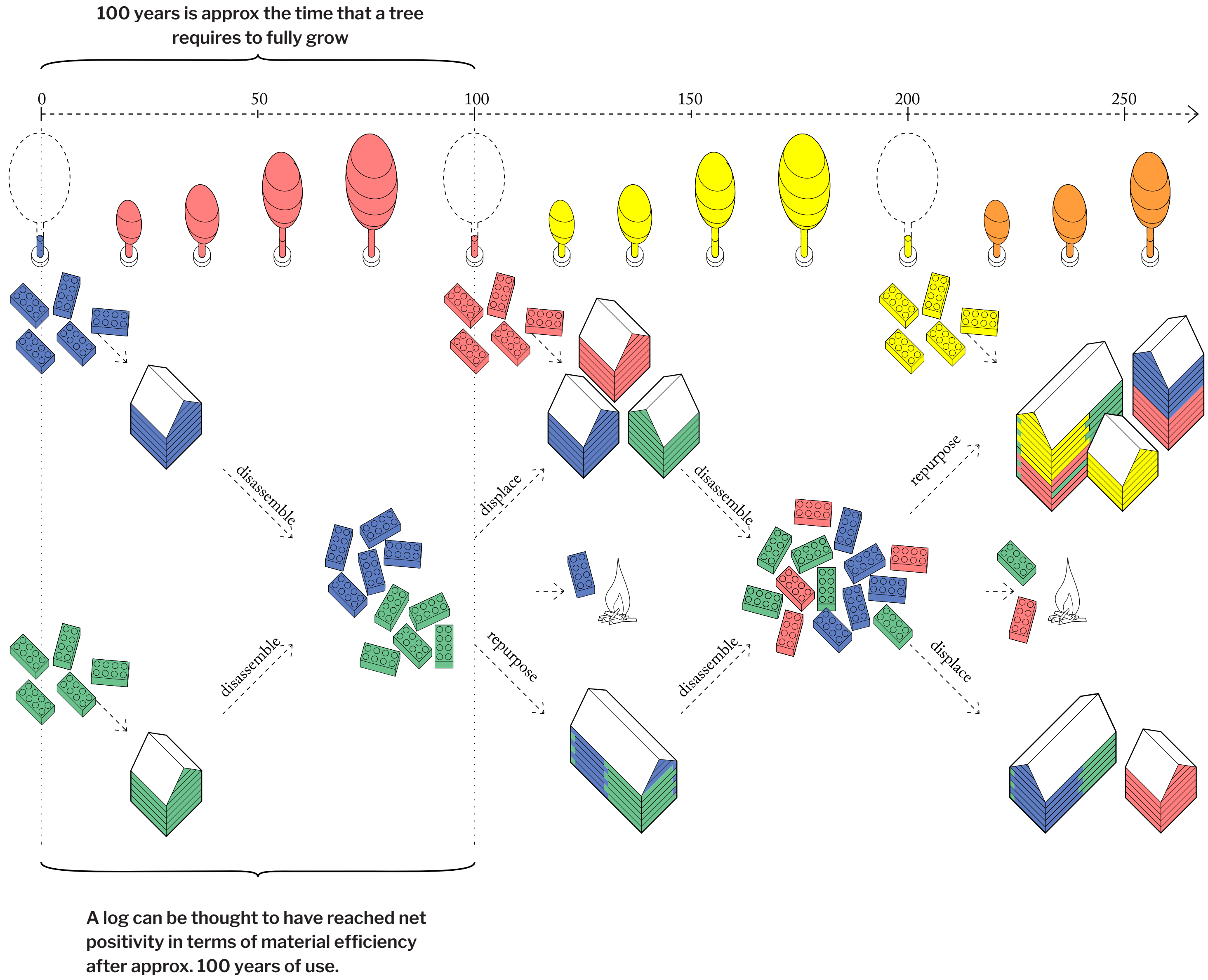

Figure 84. Diagram illustrating the material efficiency and versatility of logs as a function of time. *Livady.*

Building performance

From the angle of the traditional solutions, issues of both structural and functional categories are worthy of consideration. These issues are based on the analysis of traditional building of the Arctic and the analysis of the service life of vernacular buildings. From the angle of zero-carbon building, the focus was on the selection of applicable renewable energy technology, low-carbon materials and good structural energy-efficiency.

Resources, transportation and processing

In the traditional Arctic building, the consideration of scarcity of natural resources is evident. As the Arctic regions have, with a few exceptions, very limited infrastructure, the mitigation of the transportation costs may be achieved by using local materials as much as possible. At the same time, the low level of processing and the question of local processing technologies of the building materials is important. The resource-wise disposition of buildings and settlements therefore also becomes an important issue of consideration.

Service life, reusability and indoor environment

Traditional Arctic building consists of buildings and building components of long-lasting and, on the other hand, nearly ephemeral building materials. The most important issues of consideration for modern building are renewability and the potential of re-use of materials and components of the buildings. This means that we have to take into account modular and creative design and morphology of the building components, allowing transportability and re-assembling. Also, movable smaller buildings, a traditional feature of Arctic building, could be considered through modern performance requirements and innovative architectural design. The materials should also be non-toxic and of composting potential, which becomes important in the case of abandonment of the buildings.

For the indoor climate, important issues are solid structures and wooden indoor surfaces that diminish the quantity of microbia of the indoor climate[158], and dispense the 24 hours temperature and moisture fluctuations of the air.

Another issue, important in the Arctic and cleverly solved in traditional architecture, is tolerance to temperature fluctuations and temporary abandonment. Also, tolerance to water damage, as well as tolerance to the accumulation of snow and ice, exhibit considerable traditional solutions in the Arctic construction, and are from their structural principles worthy of consideration in modern Arctic building.

Operational and cultural issues

A key feature in the traditional construction all over the globe are understandable and conceivable structural solutions. The maintenance of the buildings, also because of the limited infrastructure, should be to maximal extent feasible by the dwellers themselves.

The multifunctionality, transformability and flexibility of buildings and rooms, in a creative and occasional manner, including the possibility to extend and reduce the heated area according to changing needs, is an important feature of traditional buildings. This can be achieved in modern building through careful and innovative design.

Last, but not the least issue of consideration, is the socio-cultural disdain for traditional solutions as rudimentary and unsuitable for modern requirements of comfort. Therefore, it is important to create examples of tradition-based buildings that meet modern standards of living and exhibit innovative and fresh architectural ideas and taste. An important issue to highlight is that the most practical structural solutions of the traditional architecture can result in modern and even better living comfort and indoor quality.

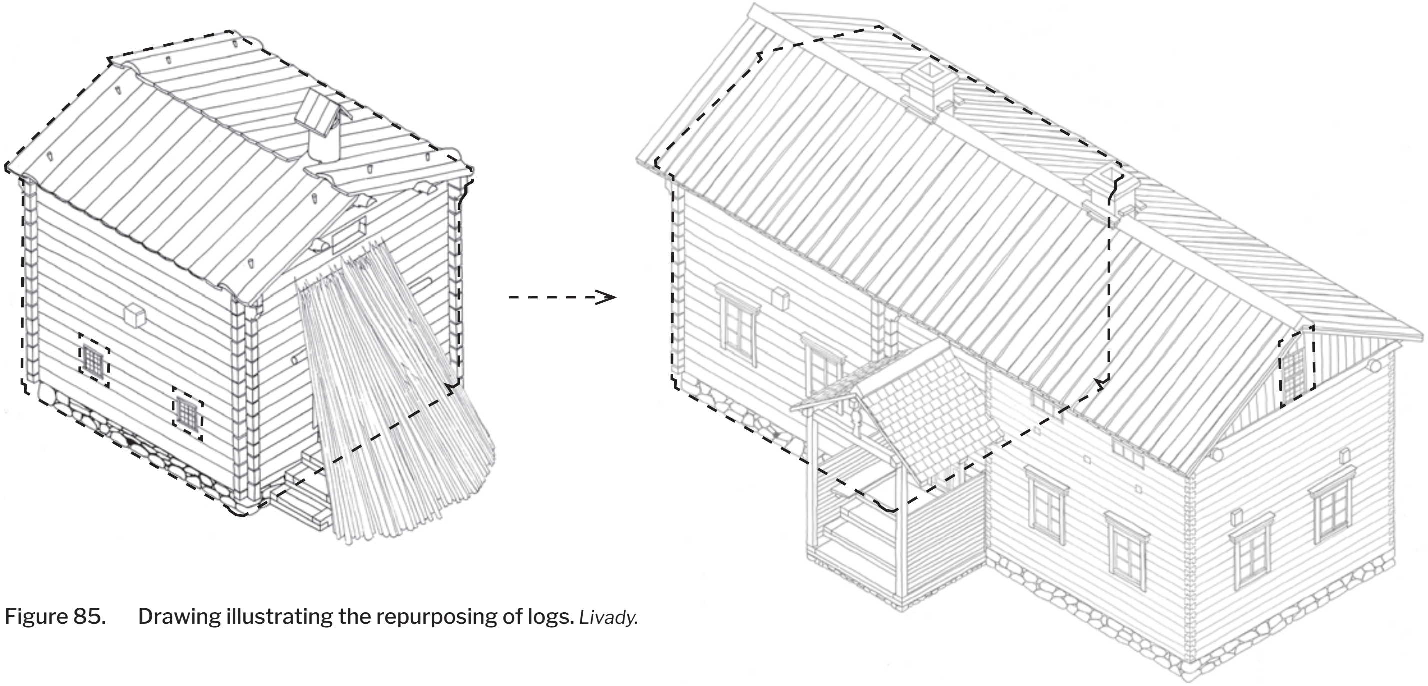

Figure 85. Drawing illustrating the repurposing of logs. *Livady.*

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[158] Vainio-Kaila, Tiina 2017. Antibacterial properties of Scots pine and Norway spruce. Aalto University Publication series DOCTORAL DISSERTATIONS 179/2017

Figure 86. Illustration of the southern facade of the Case study house. *Livady.*

Description of the case study building

The starting point of the work was a Finnish residential detached house designed for an Arctic district. The building is designed by Livady Architects. This building is used as a case to study possible alternatives for achieving sustainable and carbon neutral building targets in cold climates.

The underlying philosophy of design stems from the traditional disposition of buildings in the landscape of Arctic Finland. The case-study building can form individual units or village-like settlements, inspired by the historical constellations of Sámi villages. The availability of resources for building materials and local manufacturing are important besides the aesthetic and historical dimensions of the site(s).

The building is designed for a family-like unit but allows functional and spatial alterations that consider maximal flexibility and long functional service-life. This means zoning of spaces to different temperatures and capacity of extension to the upper floor. The changing social and functional needs are considered also in the sizes and connections of spaces. The gross floor area of the building is 130 m^2. Building total area of the envelope is 413 m^2 (roof + external walls) of which 40 m^2 are windows / glass terrace and 7 m^2 front doors.

The main constructional solution is

traditional log construction that has several advantages. First, log construction has a structural service-life of hundreds of years as standing examples show. It is a local material that has no need for long transportation or complex processes of manufacturing. Log also functions as a carbon sink, and it has versatile potential of re-use in different scales. As traditional examples show, log construction as a solid structure sustains well the Arctic climate with large amounts of water, snow and ice. In addition, log construction enables innovative and modern architectural solutions and creation of attractive modern dwellings.

Besides logs, clay, available nearby or even on site, is also used as a local material. Other materials are chosen by the principles that 1) they have as small as possible green house gas (GHG) impact and 2) are structurally sustainable and long-lasting and 3) maximize and/or enable potential for re-use and circular economy and 4) non-toxicity. A detailed list of the materials is presented in Table 14 on page 91.

The structural whole is designed to be resilient to the conditions of Arctic climate. This means mainly preventing damages caused by moisture: tolerance to water, ice and snow and drying capacity of the structures. The structural solutions are designed to be easily repairable by the dwellers themselves.

The architecture is an amalgamation of traditional constructions and modern appearance. In the structural principles the house follows the historical roots of Arctic dwellings, but it represents a 2020's interpretation of Scandinavian standards and aesthetics of living. Architecture is colorful, and the windows and the building envelope are designed to maximize the benefits of sunlight.

Regarding the end phase, a central principle creates a building that would as largely as possible contain materials that either could be re-used and/or return and decompose back to the natural cycle within a reasonable time-frame, if the building will be abandoned.

The household energy services, indoor climate and living profiles (cooking, lighting, TV's, indoor temperatures, occupant presence, hot water consumption etc.) were equal in all cases to ease the comparison of the alternative designs of the building. This was a selection related to the LCA principles, where the functional unit – in this case the indoor living profile and comfort of the occupants – is the same. Otherwise the different profiles would confuse the interpretation of the results. The basic assumption contained right from the start is that of a carbon efficient and nonwastful way of living. The indoor temperatures were defined so that the mostly used and central zones (kitchen and living room) were heated to the 21 °C, less used bed rooms to 18 °C and staircase to 5 °C. The ventilation air flows were designed so that the maximum CO_2-content in the bedrooms was always less than 1200 ppm with two persons sleeping. Household appliances were assumed to have a best possible A+++ classification and lighting was based on LED's.

Design solutions "Traditional" and "modified"

As part of this work, the objective was to develop optimized concepts for a carbon neutral house in Arctic districts. Therefore, a separate case-study building with cellulose insulation and mechanical ventilation was also designed in order to iterate a more energy-efficient solution. Alternative structures and operational systems have been assessed in order to find best combinations.

The idea was to make use of a parametric approach by comparing low-carbon solutions with a traditional solution and modified solution that both fulfil building regulations. The objective was to develop knowledge about the potentials of improved insulation, alternative renewable energy solutions and material choices, carbon storages and sinks.

Two alternative cases are studied as a starting point. In the first case (we call it 'TRADITIONAL'), the building structures were based on traditional material choices. In the modified case (we call it 'MODIFIED'), better energy-efficiency and better material efficiency is targeted. With regard to the modified case, alternative materials are used in the iteration phase to reach the carbon neutrality target. In both cases, normal comfortable indoor environment is targeted. Building cases are presented in Table 11.

	Traditional	Modified
Main target	Net carbon neutrality Traditional log building and energy-efficiency accordingly Low carbon materials (especially based on wood and local materials) District scale electricity supply + compensation Structural tolerance in the harsh climate Materials that enable reuse and recycling in various cultural and social circumstances (historical and standing examples)	Net carbon neutrality Better energy-efficiency Industrially made CLT-elements Preferring traditional solutions and materials District scale electricity supply + compensation Structural tolerance in the harsh climate
Floor area	120 m^2 (heated net area)	120 m^2 (heated net area)
Volume, roughly	289 m^3 (heated air space)	289 m^3 (heated air space)
Zoning of spaces	yes	yes
Zoning and comfort	Flexible use according to the seasons	Flexible use according to the seasons
Tolerance to temporary abandonment	yes core of building heated with wood + district scale local electricity supply	yes core of building heated with wood + district scale local electricity supply
Low risk structural solutions and low carbon materials (based on wood mainly)	yes	yes
Following traditional ways of building	Strictly	Slightly
Flexibility	yes	yes
Energy supply	District scale wind turbine (2 - 4 MW) and local PV panels and collectors	District scale wind turbine (2 - 4 MW) and local PV panels and collectors
Heating system	Ground source heat pump and wood heated stove	Ground source heat pump and wood heated stove
Floor heating	Floor heating pipes in clay layer	Liquid circulation heating in wooden/aluminum sheeting structure
Ventilation and heat recovery	Natural ventilation, (long service life, reliability, no need for electricity, allows natural microbial biodiversity)	Mechanical ventilation and heat recovery (78%)
Devices and equipment	A+++, LED lighting	A+++, LED lighting
Load bearing structures	Log structure	Structure with Cross laminated timber (CLT)

Table 11. Building cases.

	Traditional	Modified
Building location	Northern Finland, Climate Zone IV, Sodankylä, winter extreme –38 °C	
Number of residents	4 residents	
Indoor temperatures	Thermal conditions were set to be equal in both cases: -Bedrooms 18 °C -Living room-kitchen 21 °C -Bathroom 21 °C -Porch 21 °C –27°C (summer max), no mechanical cooling system	
Hot water consumption	v	
Ventilation heat recovery	-	78%
Windows:		
South	12.6 m^2	
West	4.36 m^2	
East	1.2 m^2	
North	3.47 m^2	
Balcony (Porch) glass wall:		
South	9.76 m^2	
West	5.05 m^2	
East	2.97 m^2	
U-values for building are given in next table		

Table 12. U-values (W/m^2K) of the building structures.

Material quantities

The assessment of embodied emissions bases on the building material inventory. Construction material types and amounts used in TRADITIONAL and MODIFIED buildings are shown in Table 14 on page 91.

Both buildings use onsite supplied energy (from PV panels, solar collectors, GSHP) and electricity, which is produced from district-based wind turbine. Renewable energy supply parameters are presented in Table 15 on page 92. In the GHG assessment for energy production it is assumed that service life for PV-panels, collectors and inverters is 30 years and GSHP service life is 70 years.

Energy simulation, targets and principles

The work targeted at net carbon neutrality combined with modern living comfort. The intended solution was based on very good energy-efficiency, use of renewable energy sources, district scale electricity supply and possibility for compensation.

	m^2	Traditional U-value, W/m^{2}K	Modified, U-value, W/m^{2}K
External wall 1	179	0.48	0.017
External wall 2	63.7	0.44	
Top roof	123	not relevant	not relevant
Roof	34.6	0.088	0.092
Ground floor 1	57.8	0.091	0.09V
Ground floor 2	4	0.14	0.14?
Intermediate floor 1	35	not relevant	not relevant
Intermediate floor 2	24	not relevant	not relevant
Intermediate wall 1	67	not relevant	not relevant
Intermediate wall 2	17.5	not relevant	not relevant
Windows (3 glasses)	21.63	1.0	1.0
Porch (1 glass layer)	17,77		
Doors	7.53	1.0	1.0

Table 13. Use of construction materials (including also construction waste).

	Traditional, kg/building	Modified, kg/building
Building Structures:		
Log	34 493	-
Wood	25 103	21 201
Clay plaster (wall)	1 005	-
Linseed oil	23	-
Clay brick (wall)	9 311	2 426
Roof brick	5 141	5 141
Common reed	9 265	-
Paper	72	-
Fibreboard	972	1 135
Clay plaster (floor)	18 194	-
Concrete	906	906
Foam glass	1 002	1002
Tadelakt plaster	221	-
Front doors	322	322
Inner doors	507	507
Windows	1 184	1 184
Steel columns	547	547
Plywood	395	395
Brick(chimney and fireplace)	11 907	11 907
Concrete block	4 201	4 201
Aluminium	-	455
Cellulose insulation	-	7 917
CLT (cross laminated timber)	-	16 635
Polypropylene	-	25
Plaster (Lime/cement)	-	735
Total	**124 773**	**76 642**
Water, sewage heating systems:		
Composite pipes (water pipes)	4	4
Plastic pipes (sewage)	15	15
PEX pipes (floor heating)	23	23
Pumps for hot and cold water	60	60
Ventilation pump	0	64
Total	102	166

Table 14. Use of construction materials (including also construction waste).

Figure 87. Illustration of a case-study house village. *Livady.*

For the assessing of use phase impacts, energy simulation is made for both buildings ('Traditional' and 'Modified)' with the help of IDA ICE tool[159] (version 4.8) and multi-zoning assessment. Building structure sizes, U-values and other building properties are shown in Table 12 and Table 13.

The TRADITIONAL and the MODIFIED case had partly different structures as described in Table 11 and Table 17. Both buildings had equal user profiles (the occupant behaviour and the household electricity) and indoor climate (the indoor temperature and the indoor CO_2) targets to ease the comparison. In addition, the heating system (ground source heat pump, solar collectors) but also PV-panel amount was the same in both cases.

The aspect for energy simulation was to evaluate the suitability of the design solutions related to the renewable energy production in the Arctic area. The renewable energy matching was selected as a metric for the comparison. The energy matching is defined as the hourly-calculated share of the RES production that is used in the building at the time of the RES production. The wind was assumed to be the main source of renewable energy. The role of solar energy is always auxiliary due to the nature of summer dominant production. The renewable energy solutions were:

- near-by: grid connected large scale wind power
- on-site: local solar electricity on the roof + local solar thermal on the roof.

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[159] IDA Indoor Climate and Energy (IDA ICE) web pages. Browsed Oct 21st 2019. https://www.equa.se/en/ida-ice

	Traditional, building with Solar	Modified, building with Solar
Solar panels, m²	28	28
Inverter, kW	4	4
Solar collectors, m²	8	8
Water tank, m³	0.5	0.5
GSHP (bore hold depth), m	300	160
Wind turbine, district scale, kW/ house	3.2	2.1
Peak production hours of the wind power, h	2500	2500

Table 15. Renewable energy supply parameters.

Design solution	Electricity demand		Difference	Hourly electricity grid peak		Difference
	kWh/a	kWh/ m²,a		kW	W/m²	
Traditional	11 600	96,8	47%	4,7	39	51%
Traditional Solar	10 970	91,4	38%	4,3	36	39%
Modified	7 920	66,0	0%	3,1	26	0%
Modified Solar	7 300	60,8	–8%	3,1	26	–2%
Modified Solar Passive	6 940	57,8	–12%	3,0	25	–4%

Table 16. The summary of the simulated cases and the hourly average sizing of the grid capacity. The baseline for the comparison is the modified mechanically ventilated single-family house built according to the current Finnish energy performance legislation.

Solar energy is a clean way of producing electricity, but the challenge is seasonal variation in production. Most of the production happens during the summer, when the electricity demand is smaller. The installed solar capacity does not reduce the capacity need during the high load time due to absence of solar radiation in the winter polar night. Theoretically there is an option to use seasonal storages together with large solar parks, where the summer time solar production could be stored for further use in winter, but this solutions contain two challenges. At first, the current battery technologies are far too expensive resulting at least MWh-scale batteries for one single family house using solar power only in the Arctic area. The cost of the MWh-scale batteries are many times larger than the cost of the house itself. (As an example the first in kind 0.6 MWh battery storage of Helen cost some 2 M€.[160] The second challenge is the large amount of rare metals used in battery technology resulting in increased mining and a larger environmental impact. Wind power was selected as a main renewable energy source in this study, because it has better seasonal balance in the production resulting in a better overall supply-demand match during the year cycle of seasons.

The third aspect was to evaluate the vulnerability of the heating system against the electricity blackout. The blackouts were simulated and the expected fire wood consumption with different outside air extreme conditions was calculated. The residents were living in the house center downstairs (kitchen + living room) during the blackout, which was heated with the fireplace. Other rooms were unoccupied during the black-out. The indoor temperature was 18°C in the occupied area. The loss of electricity stops the mechanical building service systems, in this case the ground source heat pump and the mechanical ventilation. In the MODIFIED house the fresh air intake for the residents is delivered by the window ventilation during the blackout.

Design solution	**System sizing (RES = Demand, yearly balance)**			
	Energy matching *)	**Peak wind (kW) **)**	**Peak solar (kW) ***)**	**Peak solar thermal (kW)***)**
Traditional	59%	5,7	0,0	0,0
Traditional Solar	50%	3,9	3,7	2,4
Modified	60%	3,9	0,0	0,0
Modified Solar	51%	2,1	3,7	2,4
Modified Solar Passive	51%	1,9	3,7	2,4

*) The energy matching is the hourly-calculated share of the RES production that is used in the building at the time of the RES production.
**) The grid RES. The capacity needed from the large-scale wind power to satisfy the electricity need for the building
***) Local RES on the roof

Table 17. The renewable energy (RES) matching of the design solutions. The system was sized so that the yearly production of the RES was equal to the yearly consumption of the building.

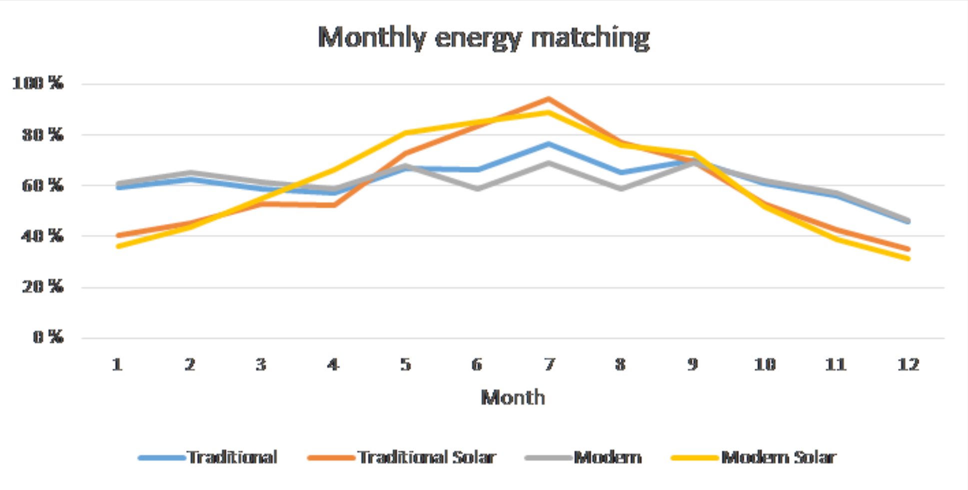

Figure 88. The monthly level renewable energy matching of the design solutions. Sizing: RES production = Demand, yearly balance. The local solar RES production weakens the yearly energy matching even though the matching is better during summer.

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[160] https://www.helen.fi/uutiset/2015/helsinkiin-pohjoismaiden-suurin-sahkovarasto)

Energy simulation results

The summary of the energy simulation results and the sizing of the grid connection are presented in the Table 16. The traditional building consumes about 50% more electric energy than the current Finnish modified building. The local RES production decreases the consumption by some 6–8% in both cases. The highly energy efficient passive solution was also tested to enhance the modified case, but the impact of the passive solution was quite small due to the ground source heat pump system, which already had a high heating efficiency, resulting minor changes in the electricity demand.

Table 17 presents the renewable energy (RES) matching of the design solutions. Due to the weather dependent nature of the wind electricity in the grid, the exact hourly match of the production and consumption is uncommon. The example of the unbalance in the traditional design solution is presented in Figure 89. Both traditional and the modified design behave the same way in relation to the utilization of the RES production, some 50–60% of the demand can be covered simultaneously by the RES. The local solar RES production weakens the yearly energy matching even though the matching is better during summer (Figure 89 and Table 17) This is due to the higher level of consumption and the low solar availability during the winter.

The results of the electricity grid blackout are presented in the Table 18. The traditional design needs approximately double the amount of firewood during the blackout compared to the modified building design.

The indoor temperature drop from the start of the blackout was also evaluated to see the impact of the loss of grid energy services on the thermal comfort of the residents. Figure 90 shows the difference between the traditional and the modified design solutions in the extreme winter conditions (outdoor temperature was –20 °C). It takes approximately 12 h for both design solutions for the indoor temperature to drop 10 °C. The differences between the solutions related to the indoor temperature drop are small because both buildings had massive wooden constructions in relation to the indoor air.

Methodology for Life cycle assessment and data sources

Figure 92 on page 97 illustrates building life cycle stages according to the modules. All highlighted stages are included in this assessment.

Environmental impact assessment considers chosen impact categories, which are calculated through characterization factors. This study focused on greenhouse gas emissions considering both embodied and operational emissions. The study also considered biogenic carbon storage.

The method for greenhouse gas assessment bases on global warming potential (IPCC 2007), which is expressed as CO$_2$ equivalent. Embodied carbon assessment is based on the biogenic carbon content of wooden materials,

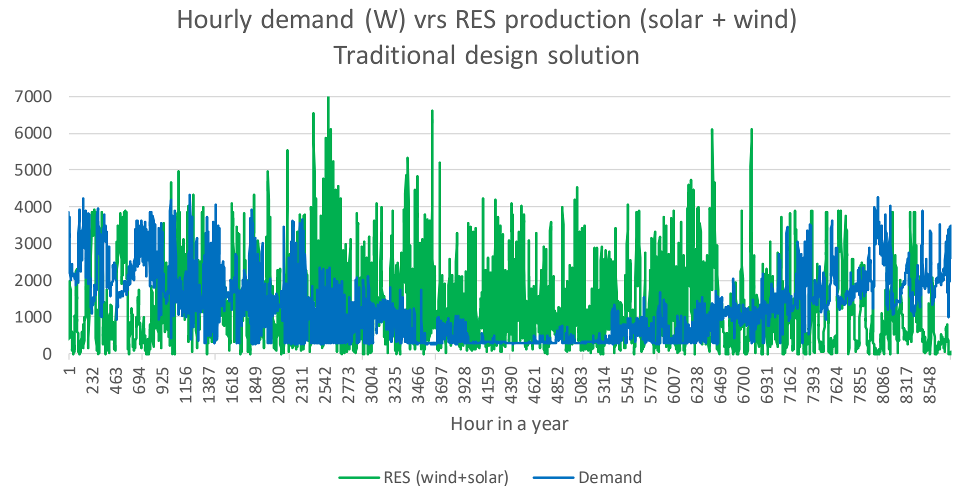

Figure 89. An example of the unbalance of the hourly renewable energy production and the demand in the traditional design solution. Sizing: RES production = Demand, yearly balance.

Tout (°C)	Wood consumption (kWh/day)		Firewood (kg/day)	
	Traditional	Modified	Traditional	Modified
0	73	37	17,6	8,9
–10	114	59	27,5	14,2
–20	154	82	37,1	19,8
–30	194	103	46,7	24,8
–40	236	125	56,9	30,1

Table 18. The daily firewood consumption during blackout of the grid electricity systems. The indoor temperature was 18 °C in the occupied kitchen-living room-bathroom area.

however the result is converted to CO_2.

Biogenic carbon content of wooden materials and ‘carbon neutrality’ is taken into account according to the rules stated in EN 16485: ‘Consideration of the biogenic carbon neutrality of wood is valid for wood from countries that have decided to account for Art. 3.4 of the Kyoto Protocol or for wood originating from forests which are operating under established certification schemes for sustainable forest management’.

This is valid for Finland and currently for all major European countries as they have reported increasing forest carbon pools under Art. 3.4 of the Kioto Protocol.

The calculation of the carbon content of wood should take into account the whole building life cycle including end of life scenarios for building demolition, transport, waste processing and disposal.

Carbon neutrality example is shown in Figure 93 in which, biogenic carbon from the forest entered to the product stage as –1 content and +1 content released in the end of life, C3 stage, through the incineration process. However, in the case when end of life process for wooden products is ‘preparation for reuse’, –1 carbon content is transferred to the next reuse case.

The GHG values used for the building materials are mainly based on the VTT ILMARI database. With regard to wind turbines, PV-panels, inverters, solar collectors, ground source heat pump (GSHP) and average electricity Finland, the data is given in Table 19.

Building construction

Construction stage takes into account all building material transportations to the building site (stage A4). VTT ILMARI, construction material database, includes impacts from average transportation distance to the construction

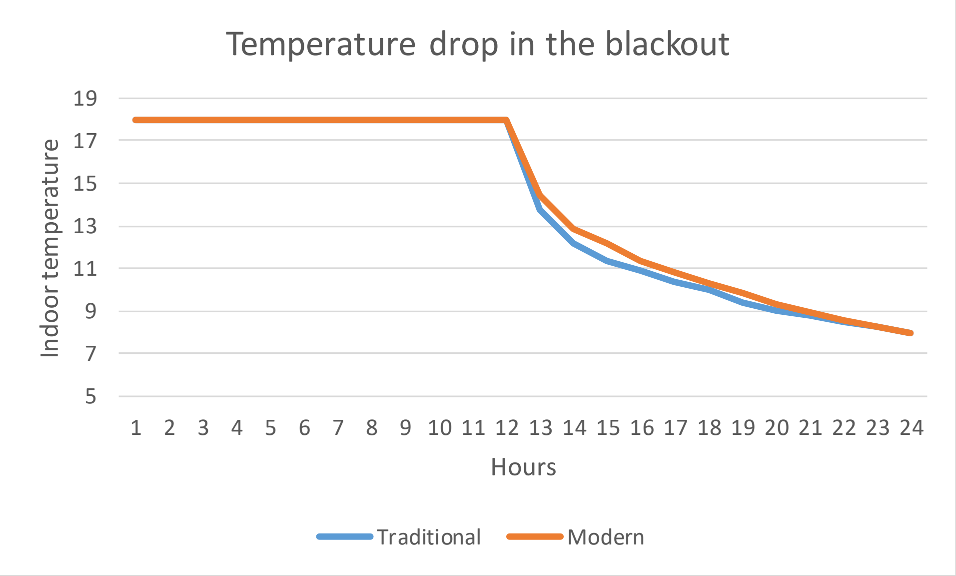

Figure 90. The indoor temperature drop in the outside extreme conditions –20 °C. The electricity outage begins at 12:00.

Used technology	kg CO_2e /unit	Data Source:
PV panels	67 kg/m²	Hammond,G., Craig, J. 2011. Inventory of Carbon & Energy (ICE). Version 2.0. Sustainable Energy Research Team (SERT. Department of Mechanical Engineering. University of Bath, UK
Inverter	7.5 kg/kW	ABB, Environmental Product declaration. https://library.e.abb.com/public/3e1b98fb5458447ec1256d8c0057f206/EPD_ACS800_630_kW_cor.pdf
Solar collectors	39,4 kg/m²	Vares et al. 2019. Impact of renewable energy technologies on the embodied and operational GHG emissions of a nearly zero energy building. Journal of Building Engineering p. 439 - 450
Wind turbine	0,014 kg/kWh	Joshua D. Rhodes, University of Texas at Austin, Energy Institute 2017 (https://cdn.factcheck.org/UploadedFiles/CO2-emissions1.jpg).
GSHP	36.4 kg/ a (bore hole depth is 300 m) and 35.7 kg/a (bore hole depth is 160 m)	Based on Vares et al. 2019. Impact of renewable energy technologies on the embodied and operational GHG emissions of a nearly zero energy building. Journal of Building Engineering p. 439 - 450 with bore hole depth modification
Average electricity	95 g/kWh	Average electricity production in Finland 2015. Based on Energy industry data about electricity production methods and consequent emission (included also transfer losses 2%) (personal communication).

Table 19. GHG’s from used technology.

Figure 91. Illustration of the East facade of the Case study house. *Livady.*

site. ILMARI has an assumption that the building site is located in Southern Finland. In this study, the construction site located in Arctic region and because of that, additional material transportation distance of 500 km was added to the assessment. It is, however, essential to consider that there is much less material transportation in the TRADITIONAL solution, since the building materials can be acquired more locally.

Materials were assumed to be transported by semi-trailer combination, with the gross mass of 40 tons and payload capacity 25 tons. GWP was calculated according to the highway driving with the 70% of payload. Vehicle emission standard based on Finnish average semi-trailer combinations used in 2016 (Lipasto 2019[161]).

Energy consumptions for those theoretical building constructions (A5) is not known. As MODIFIED building is made from large CLT based facade elements, it is assumed that energy consumption for assembling is 20 kWh/m² (this value based on one developer-measured data, from the wooden element building

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[161] Lipasto - a calculation system for traffic exhaust emissions and energy use in Finland. VTT Technical Research Centre of Finland Ltd. http://lipasto.vtt.fi/en/index.htm

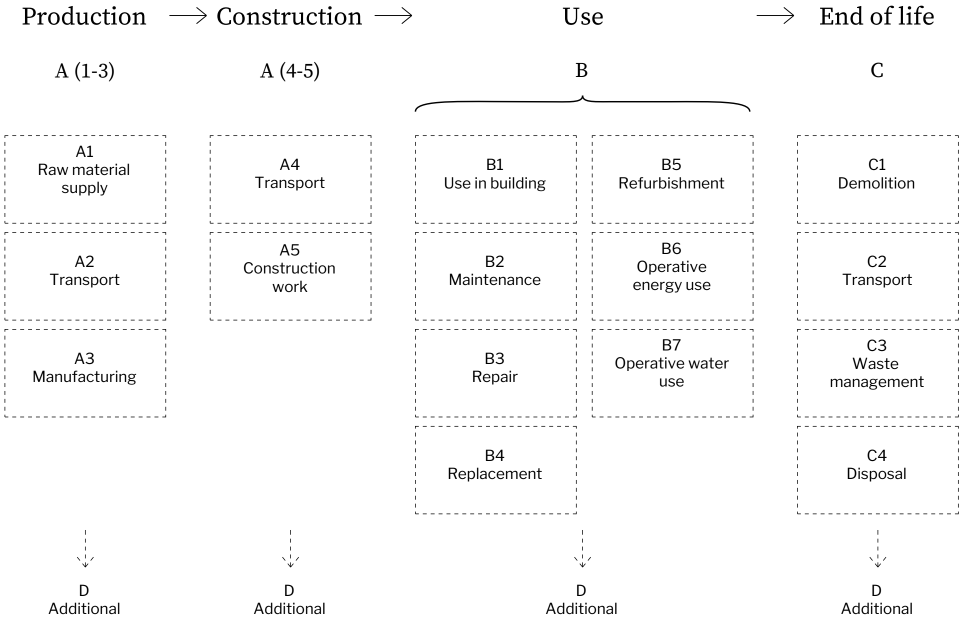

Figure 92. Life cycle stages for building assessments (EN 15978).

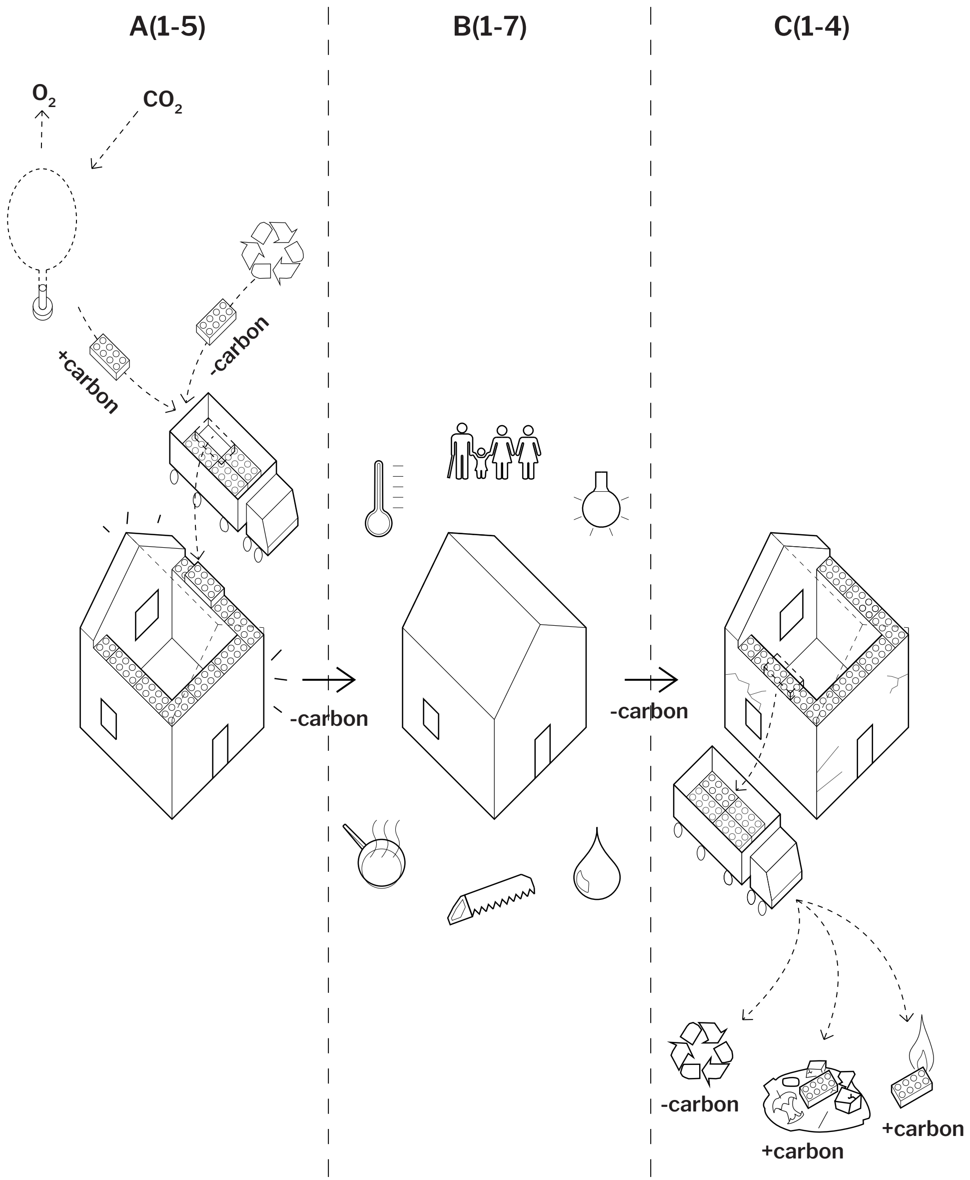

Figure 93. Characterization of carbon fluxes in case when carbon neutrality can be assumed (EN 16485). *Livady*

construction site). In this case, assembling took place in summertime and no heating, during construction period was needed. In the case of TRADITIONAL building, construction process uses a lot of handwork and thus the energy consumption for this assessed to be only half from the MODIFIED building case (10 kWh/m²).

Building refurbishment and material replacement

Reference study period for building material refurbishment and material replacements in this assessment is 60 year. This timeframe is proposed for residential buildings in Level(s) guide to Europe: A Guide to Europe's new reporting framework for sustainable buildings.[162] Table 20 proposes scenarios for building refurbishment and material replacements.

	Traditional	Modified
Facade	Treatment with linseed oil after 10 year	Facade is made from heat treatment panels and no finishing needed
Windows	Window replacement after 40 years	Window replacement after 30 years
PV panels, solar collectors, inverters	Replacement after 30 year	Replacement after 30 year
Mechanical ventilation system		Replacement after 30 year
Roof tiles	Replacement after 30 year	Replacement after 30 year

Table 20. Scenarios for buildings refurbishment and replacement.

End of building life

End of life stage is estimated using two different scenarios for wooden based materials: after building demolition wooden materials are either prepared for energy utilization (case A) or reused (case B).

Wooden material energy utilization case (A), includes following 'end of life' scenarios:

- C1 demolition of the building. Steel and aluminium materials can be recycled after the demolition.

- C2 demolition waste transportation (to the End-of-Waste stage). Demolished wood-based material transported to the wood processing place. All other materials transported to the waste sorting place. Vehicle emission standard based on Finnish average vehicles standard used in 2016 (Lipasto 2019).

- C3 Wooden material preparation for the incineration (wooden material chipping). GWP for wooden material chipping is based on the EcoInvent 3.2 database and for the wood chipping with stationary electric shipper (RER).

- C3 Building material landfill scenario is considered. Inert material treatment for landfill based on the EcoInvent 3.2 dataset. GWP calculated according to the process specific burdens (from

Building structures	TRADITIONAL		MODIFIED	
	kg CO_2e/ building	biogenic C, as CO_2/building	kg CO_2e / building	biogenic C as CO_2/building
Foundation	2 457	0	2 464	0
External wall	5 486	47 834	2 851	21 932
Roof+ eaves	2 253	12 906	2 370	9 660
Ground floor	3 239	11 135	4 528	6 736
Intermediate floor	872	8 427	1 133	5 355
Partition wall	1 628	10 515	3 091	17 075
Windows, doors, stairs	1 967	4 077	4 327	2 429
Chimney, fireplace	3 160	0	3 160	0
Other	117	632	117	632
Ventilation system	-	-	108	-
Sanitary engineering	187	-	187	-
Heating delivery pipes	43	-	43	-
Total	21 411	95 525	24 379	63 819

Table 21. GHG.s from used building materials (A1 - 4).

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[162] http://ec.europa.eu/environment/eussd/pdf/Level_publication_EN.pdf

energy, infrastructure, land use), from inert material landfilling no emissions occurred.

- C4 chips to incineration (80% efficiency).

The wooden material reuse case (end of life case B) includes all the same end of life processes as case A, except for wooden material chipping and incineration process.

Benefits and load beyond the system boundaries

According to the standard (EN 15978), informative Module D declares potential loads and benefits of secondary material, secondary fuel or recovered energy leaving the product system. Module D indicates the potential benefits of avoided future use of primary materials and fuels, while taking into account the loads associated with the recycling and recovery processes beyond the system boundary.

Both assessed building cases use onsite and district based renewable energy. Solar panels and wind turbines have an embodied impact, which is taken into account, but they avoided also average energy production. In the case of PV-panels used in Finland, Sodankylä, electricity is produced mainly from the April till September months. According to the average Electricity production in Finland from April to September, the GWP value is 72 g/kWh. This is calculated from the electricity production methods and from the year 2015.[163]

In the case of wind turbine, electricity is produced in Sodankylä all year round. Thus, it is assumed that avoided emissions are based on the average electricity production method in Finland (CO_2e for electricity production is assumed to be 0,095 g/kWh) (Table 19).

In the case of wooden material incineration for energy utilization (end of life scenario A) fossil energy use will be avoided. In this case it is assumed that it is a natural gas.

Assessment results for Life cycle analyses and GHG

Table 21 shows the GHGs for the building life cycle phase A1–A4 (EN 15804) and biogenic C-content calculated as CO_2 (EN 16449). Table 22 shows the GHGs for the building life cycle phase A5.

Table 23 shows the electricity grid demand and renewable energy production according to the building simulation cases: ‘TRADITIONAL’, ‘TRADITIONAL Solar’, ‘MODIFIED’, ‘MODIFIED Solar’ and ‘MODIFIED Solar passive’. Table 24 shows accordingly GWP values for renewable operational energy use (B6).

Results for the ‘end of life’ scenarios are given in Table 25. Table 26 shows GWP result for the building life cycle, stages A1 - C4.

Building	**Energy consumption during construction**	**kgCO_2/ kWh**	**kg CO_2e/ building**
Traditional	10 kWh/m^2	0.093	126
Modified	20 kWh/m^2	0.093	246

Table 22. Energy consumption for building construction (A5) and GHG’s.

Design solution	**Electricity grid demand kWh/a**	**Wind production**	**PV panels production**
Traditional	11 612	11 612	0
Traditional Solar	10 969	7 883W	3086
Modified	7 923	7 923	0
Modified Solar	7 298	4 212	3086
Modified Solar Passive	6 938	3 852	3086

Table 23. Energy demand and RES production.

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[163] The production data is got from Energy industries in Finland.

Discussion

LCA assessment for building construction and use phase was calculated and the indicator in the assessment was GWP. LCA methodology allows to compare building solutions only when they provide the same functional unit and performance. In this assessment, TRADITIONAL and MODIFIED building cases have different structural efficiency for external walls (U-values). To maintain equal thermal conditions, TRADITIONAL building case has higher energy demand (Table 16). Finnish case-buildings were designed to fulfil 1) the requirements to be carbon neutral building in Arctic conditions and 2) the requirements of sustainable building materials and long service life.

Building materials

Both buildings were made from wooden structures. Timber and especially logs were the dominant construction material used, and in vast regions, the only building material in Northern Europe until the Second World War. Use of wooden based materials is beneficial, as they contain biogenic carbon. In addition, log constructions are suitable for Arctic climates, as they are simple, repairable and have a long service life.

The biogenic carbon can be utilized in GWP calculations as a ‘minus’ GWP but only if the wood is collected from a forest where carbon pool is increasing. This is the case for Finland. Nevertheless, wooden material contains embodied biogenic carbon in the product phase (A1-3), although this biogenic carbon content is released in the end of life (C4) stage in case of incineration. If the material is reused, wooden material service life and carbon storage extends. Therefore long service life of structures and re-use of materials should be targeted.

Extra insulation layers minimize heat losses through the structures, but this will 1) increase the share of embodied GHGs and 2) increase the probability of moisture damage, mold and indoor climate problems. By choosing natural insulation materials, like common reed and cellulose based materials, GWP emissions from material production are normally lower than in mineral based insulation materials. However, in final assessment different thermal resistance of different insulation types needs to also be considered.

Bio-based insulations contain biogenic carbon, which could be advantageous in GWP assessments. Those materials could be also utilized in energy production processes after their service life.

Result shows that:

TRADITIONAL building contains more wooden (bio-based) materials than MODIFIED building case. This is seen in weights but also in a higher biogenic carbon content (Table 21).

In case of TRADITIONAL and MODIFIED buildings, carbon neutrality for the life cycle stages A1 - C4 is not achieved, when the end of life scenario for wooden materials was incineration (end of life case A). However, when the end of life case is material utilization (B), both assessed cases show biogenic carbon content stored after the end of life (and it is seen as ‘minus’ CO_2e) (Table 26).

Operational energy

The use of renewable energy technologies limits the emissions during the building operational phase. However, in Arctic conditions it is difficult to supply renewable energy throughout the year. This applies especially for solar energy, although solar energy is possible in warmer months (April till September). The most challenging task to solve is the intermittent hourly behavior of the RES production in relation to the energy match of the demand and production. The simulated design solutions ended up to the 60% energy matching when

Design solution	Wind	PV panels and inverters	Collectors	GSHP	Total
	kg CO_2e/a				
Traditional	163	not used	not used	36.5	199
Traditional Solar	110	64	10.7	36.5	221
Modified	111	not used	not used	35.7	147
Modified Solar	59	64	10.7	35.7	170
Modified Solar Passive	54	64	10.7	35.7	164

Table 24. GWP per annum from renewable energy production.

	C1	C2	C3	C4	Total
	kg CO_2e				
TRADITIONAL Solar (A)	2 720	417	1 140	74 355	78 632
TRADITIONAL Solar (B)	2720	417	499	0	3 636
MODIFIED Solar (A)	2 720	258	824	50 345	54 148
MODIFIED Solar (B)	2720	258	391	0	3 369

Table 25. GWP from End of Life stage.

connected to the wind power, meaning that the 40% of the energy demand would need seasonal or short-term energy storage. The current high prices of the electricity storages make them unaffordable, so the proposed solution relies on the grid connection.

Proposed building design contains roof with the slope and direction for PV panels and solar collectors. Roof space allows to include 44 m² solar collectors and 28 m² PV-panels. However, assessment considers only 28 m² PV-panels and 8 m² of collectors. This decision is made because solar energy production in the North side of roof was found ineffective (with relation to the energy production and carbon emissions).

Building energy simulation showed that Solar energy production in the South side of the roof is annually 3000 kWh/a, while in the North side it is 2279 kWh/a. In the same time GWP for the North side installations is 98 kg CO_2e/a, and in the South side is 64 kg CO_2e/a. This resulting to the fact that Solar installation GWP in the South side of the roof is only half of the North side emissions (GWP for the PV solar in the South side of the roof is 64/3000= 0.021 kg CO_2e/kWh and in the North side of the roof is 98/2279= 0.043 kg CO_2e/kWh).

Wind energy is a potential solution for renewable energy supply and PV-panels. In this assessment, PV panels and collectors installed for completing district scale wind-energy production method. Comparing GWP values for solar and wind energy production, most rational method for this Arctic region is the wind turbine. This works almost all year round and it produces energy with the lowest GWP value (0.014 kg/kWh) (Table 19).

Ground source heat pump (GSHP) is used for heating the building and it complemented with the solar collectors for producing hot water. GSHP electricity demand for heating is only ~1/3 compared to the electrical heating case.

The off-grid version was not considered in this context due to the high emissions and costs associated with batteries. The most problematic situation is the windless weather during the most severe frost, when the need for electricity storage is high. In the past, it has been shown[164] that, because of storages, the GHG emissions can increase significantly due to the manufacture, disposal and short life of batteries. In the case of off-grid, the demand for batteries in the cases examined would be in the order of 1–4 MWh/house. For example, using Li-ion water-solvent batteries in the case of wind power (Traditional), would cause about 146 tons of GHGs (manufacture + 1 change) during 60 years period of study. In the worst case, batteries cause a need to compensate 661 tonnes

	A1-A4*	**A5**	**B4-5**	**B6**	**C1-4**	**Total, A1 - C4**
	kg CO_2 e /building life cycle 60 year					
TRADITIONAL Solar (A)	–74 113	198	1 171	13 305	78 632	19 193
TRADITIONAL Solar (B)	–74 113	198	1 171	8 795	3 636	–60 313
MODIFIED Solar (A)	–39 440	396	2 341	10 171	54 148	27 616
MODIFIED Solar (B)	–39 440	396	2 341	9 869	3 369	–23 465

* incl. biogenic carbon as minus emissions

Table 26. GHG's for pre-defined life cycle stages and for the building inspection time 60 year.

	Energy production	**Unit emissions for average electricity grid**	**Case for energy, produced by average electricity**	**case for energy, produced by RES**	**Compensation (stage D)**
	kWh/a	**kg CO_2e/ kWh**	**kg CO_2e / a**	**kg CO_2e / a**	**kg CO_2e / a**
Wind energy	10 969	0.095	1 042	110	–932
Solar energy	3086	0.072	222	64	–158
Steel recovery					–18
Replacement of natural gas (in case when all wooden material will be utilized in energy production)					–625

Table 27. Benefits and loads beyond the system boundary, 'TRADITIONAL Solar' case.

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[164] Vares S, Häkkinen T, Ketomäki J, Shemeikka J & Jung N. Impact of renewable energy technologies on the embodied and operational GHG emissions of a nearly zero energy building. Journal of building engineering 22(2019)439-450

of GHGs in the case of "Traditional" and "Solar" and 512 tonnes of GHGs in the case of "Modified" and "Solar". This means that the GHG impact of batteries would be up to 10–20 times more than the house's own emissions. If the cost of the battery is assumed to be 300 €/kWh, the overall electricity cost of the one Arctic single family house would be between 0.3–1.2 M€.

To ensure the invulnerability of the heating system, wood heating is an integral part of the concept of everyday life, although fireplace materials account for a relatively high proportion of all material related emissions (about 12% in this case). This guarantees heat supply during power failures of the external grid.

If electricity supply is not temporarily working and thus geothermal energy is unavailable, firewood is much needed in the coldest times – and especially in the less insulated traditional house solution – even if only the core of the house is kept warm.

Compensation

Results show that compensation from the use of renewable energy and material salvages after the building end of life is successful. All compensations calculated for the annum bases. For material salvage case (after demolition), total benefit divided to the reference study period (60 year) and thus the result is given for annual bases. Compensation savings, in result tables (Table 27, Table 28), presented as minus emission (saved).

Both assessed buildings consume renewable energy to operate – either Wind energy or a combination of Solar and Wind energy. The assumption is, that the use of renewable energy sources compensate otherwise produced energy in Finland and consequent GWP. For wind energy it is assumed that it saves average Electricity production, and for Solar energy it is assumed that it saves Electricity production during the most favorable season (from April to the end of September). On the basis of the results TRADITIONAL Solar and MODIFIED Solar cases saving annually GWP emissions by –1090 kg CO_2e/a (932 + 158 kg CO_2e) and –792 kg CO_2e /a (634 + 158 kg CO_2e) (Table 27, Table 28).

In the same time, when the end of building life results in wooden material incineration and utilization, emissions from natural gas production have also been saved. According to the results,

	Energy production	Unit emissions for electricity kg	Case for energy, produced by average electricity	Case for energy, produced by RES	Compensation (stage D)
	kWh/a	kg CO_2e/ kWh	kg CO_2e / a	kg CO_2e / a	kg CO_2e / a
Wind energy	7298	0.095	693	59	–634
Solar energy	3086	0.072	222	64	–158
Steel recovery					–18
Aluminium recovery					- 24
Replacement of natural gas (in case when all wooden material will be utilized in energy production)					–423

Table 28. Benefits and loads beyond the system boundary, 'MODIFIED Solar' case.

Figure 94. Entrance to the patio of the Case study House. *Livady.*

annually saved GWP for TRADITIONAL building is –625 kg/a, and for MODIFIED building case –423 kg/a (Table 27, Table 28).

Assessment considered that steel and aluminum materials are salvaged after the building service life and demolition. According to the results for the both building cases GWP savings from steel recycling is –18 kg/a. In a MODIFIED building case also aluminum is used and salvaged, this resulting to the GWP saving –24 kg/a (Table 27, Table 28).

End of life scenario, case B, considered that also all wooden materials are salvaged for the secondary use. For this case, no material compensation was assessed, only the stored biogenic carbon content was take into account. It is essential to highlight the importance of the secondary use of building components. Assessment shows that this was the most remarkable factor affecting the GHG emissions of both case-study buildings. This result points out the need for the salvage of components and materials after demolition for reuse. Thus, the importance of long service-life of buildings and the use of tolerable and sustainable structures is high. To meet building carbon neutrality for harsh Nordic conditions, building construction should use materials, which have low carbon emissions.

Arctic regions form a sparsely populated area, where climatic conditions and natural resources vary a lot. Universal solutions for carbon-neutral and sustainable Arctic building probably do not exist, but this study shows some general guidelines that may be tested elsewhere. This means researching traditional solutions and making new designs based on the long history and valuable information about adaptation of past generations to local climate and resources.

Figure 95. Illustration of the Case study house in the evening. *Livady.*

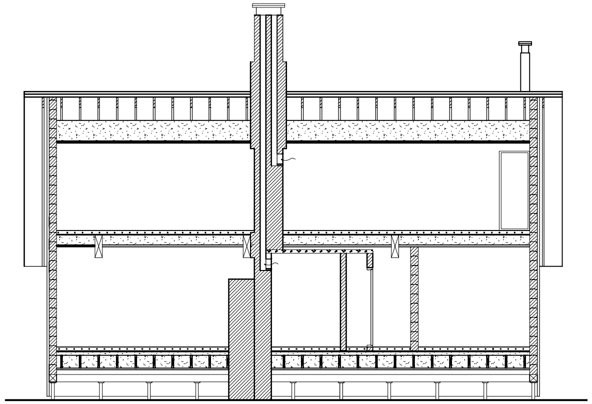

Figure 96. Section of the Case study house. *Livady.*

Canada

Design process with Inuit of a prototype for northern housing

Thanks to the collaboration of the Kativik Municipal Housing Bureau, Mativik Corporation, the Kativik Regional Government and the Société d'habitation du Québec (SHQ), a semi-detached building was recently constructed in Quaqtaq (59.97°N, 69.62°W) in order to become a prototype of northern housing for the Nunavik communities. Two principal criteria were used to guide the design process: (i) to design layouts that are adapted to Inuit's culture and lifestyle, and (ii) to develop a novel building system with high energy performance.

A design charrette involving Inuit was organized. It consisted in a 3-day workshop in which Inuit could directly interact with building stakeholders. The methodology employed for the workshop was to go through each common indoor activity (e.g., cooking, eating, cleaning, sleeping, tidying…), as well as outdoor activities (e.g., maintenance, socializing…). This process followed six steps: the identification of needs for each activity, the definition of spaces in houses, the identification of aesthetics and practical expectations, the hope regarding building implementation, the representation of the 'ideal' dwelling and the presentation of results.

Various solutions which emerged from the design charrette were applied to the design of the prototype built in Quaqtaq. One of them is the implementation of a "cold porch", an unheated space that both protects the main entrance from the harsh weather and gives occupants a place to store hunting and fishing gear. This porch is equipped with a stainless steel counter that can be used to clean fish and equipment or to work on animal skins. Each dwelling has a large central living area (53.4 m^2) with mobile counters, so that occupants can push them out of the way when preparing traditional suppers, which are taken sitting on the floor. There is also a second fire escape, which is not typical, since Inuit feared being trapped inside a burning building. The addition of balconies, of large windows and of supplemental storage spaces are other solutions that were applied to the prototype thanks to the recommendations emerging from the design charrette.

Description of the building and its surrounding climate

The case study building contains two 2-bedroom dwellings that each have a floor area of 99.0 m^2. Located right on the meeting point of the Ungava Bay and the Hudson Strait, Quaqtaq is one of the 14 communities located in Nunavik in the province of Quebec. It averages 8,800 heating degree-days a year. Figure 97 summarizes the weather conditions observed in Quaqtaq by displaying average monthly solar radiation and air temperature. Winters are particularly harsh with an average temperature of –20.0°C from the beginning of January to the end of March. In summer, air temperature is on average 6.7°C with temperature peaks reaching around 20°C. Solar radiation is minimal (0.30 kWh/m^{2}day) from November to January as nights are quite long – in December 21st, daylength

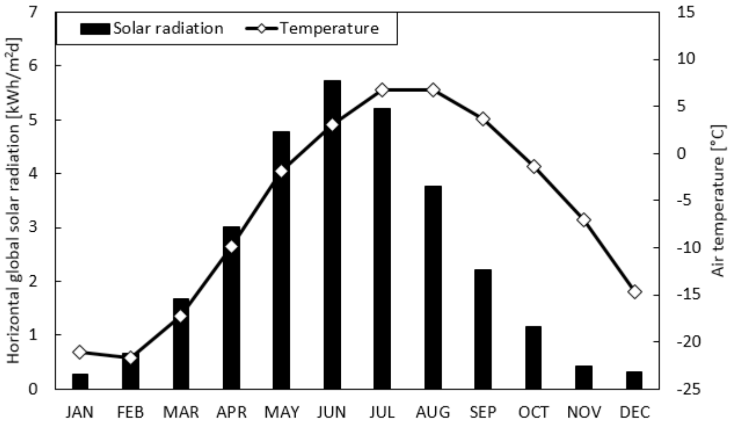

Figure 97. Monthly solar radiation and mean air temperature in Quaqtaq.

is only 5 hours and 31 minutes. On the other hand, with daylength reaching 19 hours and 17 minutes on June 21st, solar energy is plenty during the summer. Solar radiation reaches 5.73 kWh/m^2day in June. There is 19 times more solar radiation in June than in January. In the southern regions of Canada, this ratio is approximately 5, which demonstrates how variable solar radiation is in the Arctic region.

The case study building is built on steel pilings driven into the ground. This prevents the permafrost from melting due the heat coming from the building, which could seriously damage the building. In order to reduce the energy demand of the building, a highly insulated and airtight envelope was designed – the RSI value for vertical walls is 9.556. Triple-glazed windows were installed. As shown in Figure 92, in addition to the two dwellings, there is a single HVAC room (11.9 m^2). In this room, a glycol-based boiler (capacity of 47 kW) is connected with a two-coil hot water tank (capacity of 450 L). This tank acts both to distribute domestic hot water (DHW) to occupants and as a buffer tank so that the heating system delivers high-level thermal comfort. Each dwelling has its own specific mechanical ventilation system. Supply air in these systems (capacity of 28 L/s of air per dwelling) is heated by two heating coils (one before and the other after the HRV units) and space heating is covered by hot water radiators. Two other water tanks are located within the thermal envelope of the building – one for clean water (capacity of 4,545 L) and the other for grey water (capacity of 3,995 L). These tanks are placed below the bathrooms so that heat released by grey water can warm these spaces and reduce the heating demand. They are typically filled (for the clean water tank) or drained (grey water tank) every day by delivery trucks. Artificial lighting is obtained with LEDs.

The first column of Table 29 summarizes the architectural and HVAC features of the prototype. This table lists diesel as being the energy source for the building. Since they are remote, Nunavik communities are not connected to

Figure 98. South facade of the prototype and simplified floor plan of the building.
Société d'habitation du Québec (www.habitation.gouv.qc.ca)

	Prototype (SC1)	Building with "typical" insulation (SC2)	Building with "typical" insulation, airtightness and HVAC system (SC3)
Floor area [m²]	209.87		
Volume [m³]	845.27		
Energy supply	Diesel		
Heating system	Glycol-based boiler (efficiency of 87%) connected to hot water radiators		Boiler with an efficiency of 68%
Ventilation and heat recovery	Mechanical ventilation with 2 HRV units (efficiency of 85%)		HRV units with efficiency of 70%
Number of PV panels	PV0: 0 ; PV1: 116 ; PV2: 52 ; PV3: 48 ; PV4: 21		
Number of inverters	PV0: 0 ; PV1: 5 ; PV2: 2 ; PV3: 2 ; PV4: 1		
Roof area [m²]	226.25		
Roof materials	Sealed roof Polyisocyanurate	Ventilated roof Cellulose	
Roof u-value [W/m²K]	0.082	0.111	
Vertical walls area [m²]	233.71		
Vertical walls materials	Double wooden framing Fibreglass insulation Polystyren	Simple wooden framing Fibreglass insulation Polystyren	
Vertical walls U-value [W/m²K]	0.105	0.188	
Floor materials	Fibreglass insulation Polystyren	Cellulose Polystyren	
Floor U-value [W/m²K]	0.097	0.122	
Windows surface area [m²]	South: 19.38 / West: 1.81 / North: 10.86 / East: 1.81		
Windows U-value [W/m²K]	0.813 (Triple glazing)	1.250 (Double glazing)	
Doors U-value [W/m²K]	0.568	1.818	

Table 29. Architectural and HVAC systems of the case study building and the different scenarios that were studied.

the main Quebec energy grid, so diesel is the only fuel used both to provide heat to buildings and to generate electricity via the local diesel power plant. A heating value of 10.5 kWh per liters of diesel was used in this study[165].

A monitoring campaign started on November 2016 to document the thermal behavior of the building. A total of 49 different measurement points are continuously registered since then. The temperature in all rooms of both dwellings, along with CO_2 level and relative humidity in the central living area, were measured at a 15-min frequency. In the HVAC room, temperatures in each water tanks and water levels are also acquired with this frequency. Energy consumption (diesel demand of whole building, electricity demand of each dwelling and HVAC room, total use of hot water) and openings of doors, windows and exhaust fans (bathroom, kitchen and dryer) are registered for each day.

The monitoring of the building showed that it annually consumes 215 kWh of heat per square meter of floor area. Preconstruction simulations predicted a consumption of 128 kWh/m² for heating, meaning that the building consumes 68% more heat than initially expected. Such discrepancies between reality and simulations are frequently

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[165] The Engineering Toolbox. Fuels – Higher and lower calorific values. https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

reported in literature, a phenomena known as the “energy performance gap”.[166] This energy performance gap is usually explained by HVAC system defects and/or occupants using the building (temperature set point, window opening, etc.) differently than what was assumed. For instance, it was assumed in preconstruction simulations that windows were always closed in winter. However, observations showed that windows were frequently opened, which in turn, increases the energy required for heating.

Presentation of all studied scenarios

In this study, the performance of the prototype is compared to other variants of the same building that were simulated. A total of 11 scenarios were considered. The first scenario is the prototype as built (Scenario 1 - SC 1). The next 4 scenarios correspond to the current prototype to which photovoltaic solar (PV) panels were added. The difference between these scenarios is the number of panels installed: PV1 – Panels on all elements of the facade, PV2 - Panels only on the roof and south facade, PV3 - Panels on the roof and partly on south facade to generate annually as much electricity as consumed (i.e. 15,033 kWh) and PV4 - Panels only on the roof. As shown in Table 29, the configuration PV1 requires a total of 116 PV panels (1.95 m^2 each) and 5 10-kW inverters. These values respectively are 52 and 2 for configuration PV2, 48 and 2 for PV3, and 21 and 1 for PV4. Additionally, a building with a different energy performance level was studied. This building has an envelope that is closer to typical houses in Nunavik. It is less insulated than the prototype and thus consumes more energy for space heating. The performance of this building was calculated without and with PV panels. Finally, a third class of building was also studied (SC 3). The envelope of this building also has the same “typical” level of insulation as the building in SC 2, but is less airtight. SC 3 also uses “typical” HVAC systems that are less efficient than the ones of the other scenarios. Each of these scenarios were analyzed by determining their respective energy consumption from simulations and their carbon emissions by a life cycle analysis.

Parameter	Description
Population	5 peoples (3 in dwelling 1, 2 in dwelling 2)
Temperature set point [°C]	20
Window opening	Only if it is warmer outside or it is too warm inside
DHW consumption [L/day-person]	25
Electricity consumption [kWh/day]	41.1

Table 30. Simulated occupant behaviour for all scenarios.

Building energy demand simulations

Methodology

To compute the energy consumption of the build under each scenario, energy models were developed using the dynamic energy simulation software TRNSYS[167]. Measured data was used to calibrate the numerical model of the prototype. Uncertain building parameters, such as infiltration rates and air capacitance, were adjusted in the SC1 model until the model predicted energy demand and temperature levels that matched with observed values from the real building. Once calibrated, the model predicted a heating demand of 201.1 kWh/m^2 per year, which is an underestimation of 6% of the real building consumption. The average indoor temperature difference between measurements and simulation was 0.4°C, so the model is able to accurately depict both the indoor temperatures and the energy consumption of the building. Once the SC1 model was calibrated, it was used as a starting point for developing the other models.

Since occupants affect the energy performance of a dwelling, it was important for the sake of comparison to use the same occupant behavior profile for all simulations. This profile is described in Table 30. The indoor tem-

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[166] Willan et al. Talking abouts targets : How construction discourses of theory and reality represent the energy performance gap in the United Kingdom. https://doi.org/10.1016/j.erss.2019.101330

[167] http://www.trnsys.com/index.html

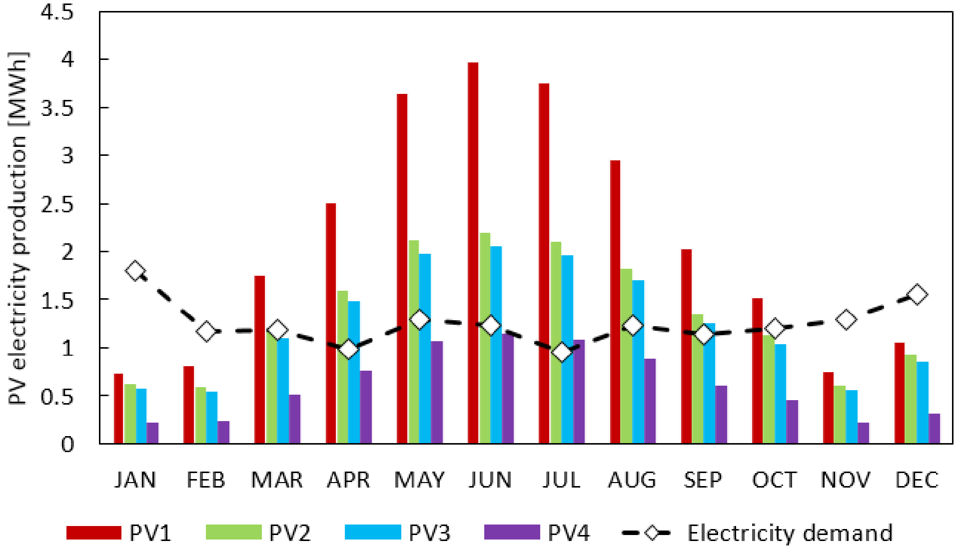

Figure 99. Monthly PV electricity production for all scenarios compared to the demand.

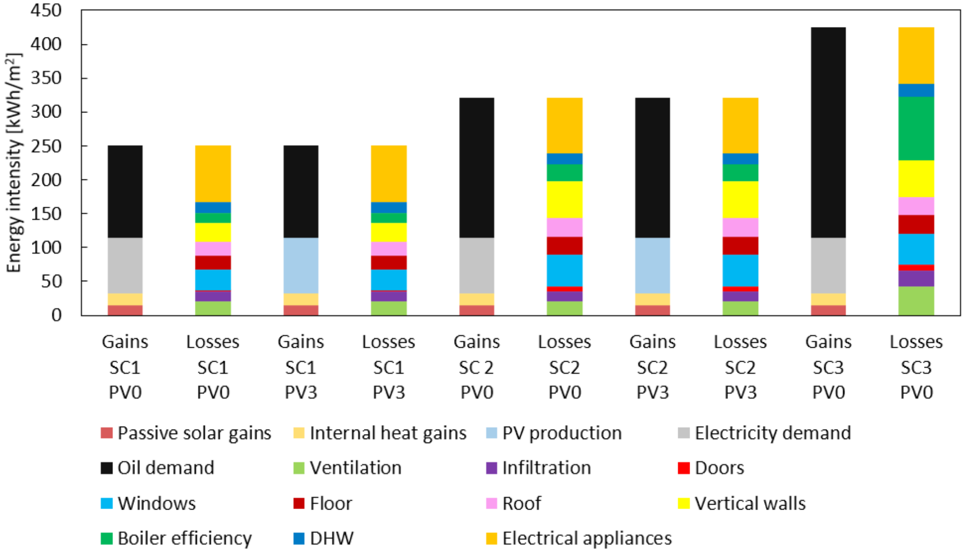

Figure 100. Energy balance for SC1, SC2 and SC3. PVs are sized to match with the annual electricity demand of the building.

perature of 20°C is the value used by the Passive House Institute for certifications of buildings[168]. The DHW consumption rate of 25 L/day per person is also taken from the value proposed by the Passive House Institute and is close to the actual demand from the monitored building (24.4 L/day per person). As for electricity demand, the consumption from the real building was directly used in the simulation.

As for the estimation of the production of electricity from PV panels, the web-based calculator PVWatts, developed by the National Renewable Energy Laboratory (NREL) in USA, was used to estimate the monthly production of such panels[169]. PV panels considered in this study are made of crystalline silicon and covered by a glass with anti-reflective coating. They have a relatively high efficiency of 19%. System losses, which accounts for shadows, wire, installation imperfections and lighting degradation, amount to 12.3% of the production. The temperature coefficient of power was –0.35%/°C. These values were suggested by PVWatts. Since the roof of the building has a relatively small inclination (5°), panels on the roof were tilted at an angle of 40° as if mounted on a structure. The surface area of the PV panels on the roof were calculated so that it would be physically possible to fit all PV panels on the roof with an angle of 40°. A minimal angle of 40° is often recommended to avoid snow accumulation on the panel. PVs on the facades were assumed to be vertical.

Our simulations suppose that throughout the year the local micro-grid is able to take or buy excesses of electricity at times when PV panels produce more electricity than the building require and to provide electricity when production cannot match with the demand. This assumption means that no electricity storage is implemented in the model. Such an hypothesis only works if few such buildings are connected to the micro-grid. Otherwise, there might be problems with the stability of the micro-grid and diesel engines have a low efficiency a low part-load. The calculated electricity production values can thus be seen as an upper bound of electricity that can be produced and these values are not sustainable for analyzing whole communities without using storage systems such as batteries.

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[168] Passive House Institute. Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard.

[169] https://pvwatts.nrel.gov/

Results for energy production and consumption for all scenarios

Figure 98 presents the monthly electricity production from the PV panels for all studied configurations. With configuration PV1 (116 panels), 25,521 kWh was produced directly onsite. Since the annual demand for electricity is 15,034 kWh, such a production means that the building gives a net balance of 10,487 kWh to the micro-grid each year. Despite such high production rate, Figure 98 also shows that configuration PV1 is unable to match the demand for electricity from November to February. The lack of solar radiation during these four months makes it impossible to generate enough electricity, even if the building facade is completely covered with PV panels. On the other hand, configuration PV4, which only puts panels on the roof, is only able to produce enough electricity to match the monthly demand in July. This reinforces that energy storage would be useful in the North to maximise the full potential of solar energy. Detailed information regarding the annual production of electricity is listed in Table 31. Unsurprisingly, configuration A produces more electricity than the other configurations. However, it is also the least efficient configuration in terms of produced electricity per square meter of PV panels.

As for the consumption of heat, the TRNSYS model yielded, with the occupant profile, a heating demand of 119.7 kWh/m^2 for the prototype, which translates into a total consumption of 21,833 kWh. When changing the building envelope for a more 'typical' envelope (i.e., the envelope of SC2), the heating demand goes up to 191.1 kWh/m^2 (34,856 kWh). The change to a less insulated envelope increased by 56.8% the heating demand. The other type of building (SC3), with a less airtight envelope and with less efficient HVAC systems, has a simulated heating demand of 290.4 kWh/m^2 (52,969 kWh). Heat required for DHW purposes amount to 16.0 kWh/m^2 (2,918 kWh) in SC1 and SC2 and to 19.9 kWh/m^2 (3,630 kWh) in SC3. Annual diesel consumption, which is required for space heating and DHW, is thus 2,721 L for SC1, 4,152 L (52.5% increase from prototype) for SC2 and 6,221 L for SC3 (128.6% increase from prototype).

The overall energy balance of all scenarios is displayed in Figure 100 For each scenario, the energy gains and losses of the building are presented in stacked bars. Note that for the sake of simplicity, only the setup of PV panels that produces as much energy as consumed (configuration PV3) is presented in the figure. Minimizing diesel (black bars) and electricity (grey bars) consumption can be achieved by increasing the passive solar gains, the internal heat gains and onsite electricity production or by reducing energy losses. For SC1-PV3 and SC2-PV3, the grey bars that represent electricity demand are completely replaced by PV production, which represents a high reduction of energy consumption, particularly for the SC1 building. Major energy losses for all scenarios are the electricity consumed by households and heat losses through vertical walls and windows. For SC3 the lack of efficiency of the boiler is the most important reason for energy losses. In the prototype, there is more loss through the windows (30.6 kWh/m^2 of floor area) than through vertical walls (27.16 kWh/m^2) although the surface area of vertical walls is 8 times higher than the ones of windows. However, it should be note that windows allow for passive solar gains of 14.6 kWh/m^2 for all scenarios and can help to reduce artificial lighting.

Configuration	Number of panels	Annual electricity production [kWh]	Annual net electricity consumption [kWh]	Annual electricity production per surface area of panels [kWh/m^2]
PV1	116	25,521	–10,487	112.8
PV2	52	16,223	–1,189	160.0
PV3	48	15,085	–51	161.2
PV4	21	7,497	7,537	183.1

Table 31. Produced electricity by PV panels for all considered configurations.

Life cycle assessment

Methodology

Life Cycle Assessment (LCA) is a systems approach used to assess the potential environmental impacts of the entire life cycle of a product or service, taking into account its functionality. This method is defined by the ISO 14040 and ISO 14044 standards.[170]

LCA as defined by the ISO standards was applied in this study to the 11 scenarios. The functional unit is 210 m² gross floor area for a service life of 60 years, which refers to a house over its lifetime. There are four main stages in the house's life cycle: the supply stage (raw materials extraction, materials manufacturing, energy production), the transportation stage from the factory to Nunavik, the operations stage and the end-of-life stage. Operations include electricity and heat consumptions as well as refurbishment for some materials.

For scenarios with PV panels, the totality or a part of the electricity consumption is generated from PV panels. If the electricity production is greater than the consumption, part of this production is fed to the local micro-grid. In order to keep all scenarios functionally equivalent, systems expansion is introduced as recommended by the ISO standards. System expansion consists in subtracting from the impact of scenarios the impact of an equivalent quantity of electricity generated from the average mix in Nunavik, which thus becomes an avoided impact. To facilitate the results' interpretation, this avoided impact will be given separately from the scenarios' life cycle impacts.

The construction and demolition stages have been neglected, as well as the energy and mechanical systems of the house. Occupants' activities other than electricity and heating needs are not included as they are considered identical for all scenarios.

Primary data on materials (type, quantities) were obtained from the plans and information provided by the project's partners. Missing data, such as some components' dimensions and material densities, were retrieved from manufacturers' technical sheets and literature. Transportation distances were estimated from the location of the main manufacturers for each material on Google Maps, taking into account that transport to Nunavik is mostly by boat, departing from the port of Sainte-Catherine in the Montreal region. They are shown in Tab 4.4. The table also indicates the main assumptions regarding materials service lives (influencing their replacement rate) and their end-of-life management. Given the great uncertainty in predicting end-of-life scenarios in 60 years (and even more so in an isolated region such as Nunavik), two end-of-life scenarios were assessed. This first considers landfilling for all materials, except for softwood which is burnt. This scenario is pessimistic. The second includes a 100% recycling rate for wood, steel and aluminium elements, and is thus optimistic.

Secondary data are taken from the Ecoinvent database v.3.5, choosing the "allocation, cut-off by classification" approach. Ecoinvent is considered the most suitable database for LCA model-

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[170] International Organization for Standardization (ISO), 2006a. IS014044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines

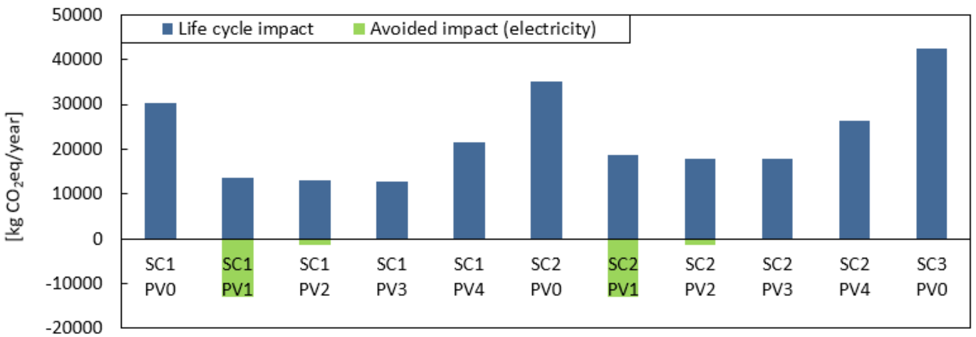

Figure 101. Impact on climate change of the different scenarios.

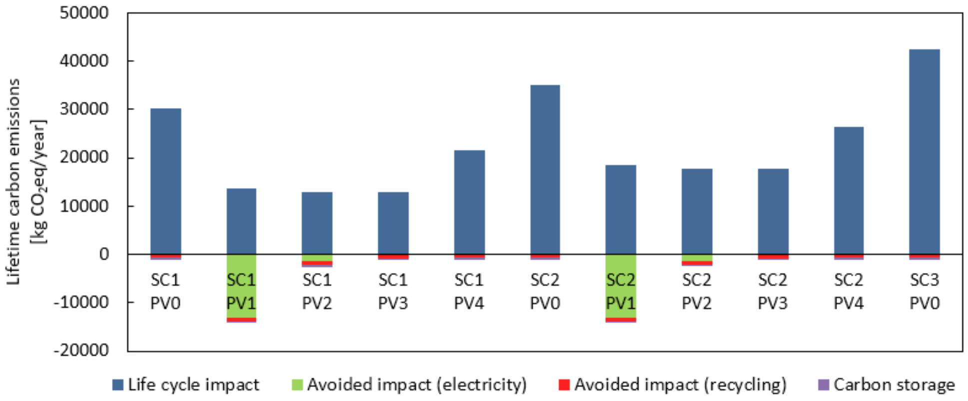

Figure 102. Impact on climate change - optimistic end-of-life management.

Materials	Distances	Service life [year]	End of life	
			Pessimistic	Optimistic
Softwood, plywood, OSB panels	Truck: 300 km Boat: 4000 km	60	Open burning (softwood), landfilling (plywood, OSB)	Recycling (softwood), landfilling (plywood, OSB)
Extruded polystyrene, fiberglass wool	Truck: 50 km Boat: 4000 km	40	Landfilling	Landfilling
Mineral wool / cellulose	Truck: 100 km Boat: 4000 km	40	Landfilling	Landfilling
Gypsum fiberboards	Truck: 50 km Boat: 4000 km	60	Landfilling	Landfilling
Steel / aluminium	Truck: 1000 km Boat: 4000 km	60 (structural steel) / 40 (steel and aluminium cladding)	Landfilling	Recycling
Glass	Truck: 300 km Boat: 4000 km	30	Landfilling	Landfilling

Table 32. Main assumptions on the life cycle of construction materials.

	Life cycle impact (kg CO_2eq/year)	Avoided impact (kg CO_2eq/year)	Variation from the base case scenario (SC1-PV0)
SC1-PV0	30,281		-
SC1-PV1	13,737	–13,020	–55%
SC1-PV2	12,964	–1,476	–57%
SC1-PV3	12,869	–63	–58%
SC1-PV4	21,596		–29%
SC2-PV0	35,143		16%
SC2-PV1	18,599	–13,020	–39%
SC2-PV2	17,826	–1,476	–41%
SC2-PV3	17,732	–63	–41%
SC2-PV4	26,459		–13%
SC3-PV0	42,526		40%

Table 33. Impacts on climate change and variations from the base case scenario (SC1-PV0).

ling of buildings[171]. It should be noted that it includes regionalized Quebec datasets for wood, concrete and OSB panels. In the case of the electricity mix, a dataset specific to each Canadian province and territory exists in Ecoinvent, including Nunavut, whose current energy system based on diesel power plants supplying communities not connected to the main grid can be considered similar to the one in Nunavik[172]. Moreover, mineral wool was not available as such in Ecoinvent v.3.5, it was then substituted in the database by the process of rock wool.

As mentioned by the ISO standards, but also recommended by the European standard EN 15978, the allocation procedure for reuse and recycling follows a systems expansion approach, where 1) impact and benefits of recycling are allocated to the lifecycle that makes the materials available for recycling and 2) the benefits are calculated as the avoided impact allowed by the materials' reuse and recycling at the house's end of life (module D in EN15978).

When softwood is recycled, it is assumed to replace the production of wood chips (further used in particleboards production for example). Scrap aluminium is assumed to replace primary aluminium and scrap steel displace the production of primary steel (blast furnace).

The life cycle impact assessment is presented for the climate change category only. The characterization method used is the method developed by the Intergovernmental Panel on Climate Change (IPCC) with a time horizon of 60 years[173]. Biogenic carbon uptake from wood products were included in the calculations, with a characterization factor of –1 at the production stage and +1 at the end of life, thus assuming carbon neutrality over the lifecycle. An exception occurs when wood is reused or recycled, like in the optimistic scenario. Then, carbon storage is considered effective, which results in a credit to the house's life cycle. The carbon content of softwood used in this study is assumed equal to 795 kg CO_2 eq/m^3, which derives from an EPD of North-American softwood lumber by the American and Canadian wood councils. Finally, all impact modelling was carried out using SimaPro software v9.

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[171] Martinez-Rocamora et al., LCA databases focused on construction materials: A review, 2016 https://doi.org/https://doi.org/10.1016/j.rser.2015.12.243

[172] Ministère de l'énergie et des Ressources Naturelles du Québec, Politique énergétique 2016–2025, 2015.

[173] Intergovernmental Panel on Climate Change, Calculation of mitigation potential/carbon footprint/Life Cycle Assesment (LCA), including application of 2006 IPCC guidelines, 2013.

Results for all scenarios:

Figure 101 presents the results on climate change for all the scenarios, with a pessimistic end-of-life management. The “life cycle impact” section refers to the life cycle impact of the house from raw material extraction to end of life. The “avoided impact (electricity)” section quantifies the avoided impact due to feeding part of the solar panels’ production to the electricity grid.

Considering only life cycle impacts,Figure 101 shows that the scenario with the least impact on climate change is scenario SC1-PV3, followed very closely by SC1-PV2 and SC1-PV1. These scenarios represent a 58%, 57% and 55% reduction in impact respectively, compared to the baseline (SC1-PV0), as shown inTable 33. The impact of SC1-PV4 is midway (–29% compared to baseline), reflecting its position as a compromise between a 100% solar and 100% fossil fuel electricity supply.

However, SC1-PV1 (along with SC2-PV1) has the greatest potential for avoided impact due to a greater surplus of solar energy. Indeed, if the building feds all excess electricity produced to the local micro-grid, an equivalent production of electricity from the regional mix can be avoided. SC1-PV1 clearly becomes the most advantageous scenario under this hypothesis. The net impact reduction compared to SC1-PV0 rises to 98%, compared to a reduction of 62% for scenario SC1-PV2 and of 58% for scenario SC1-PV3.

The impact of SC2-PV0 is greater than SC2-PV0 (+16%), thus suggesting environmental benefits for opting for measures aimed at a greater energy efficiency and reduction of heating needs for this region. Impact of Scenarios SC2-PV1-4 in relation to SC2-PV0 is the same as the impact of SC1-PV1-4 in relation to SC1-PV0 since the same assumptions are applied regarding electricity consumption. SC3-PV0, with its inefficient heating system and less airtight envelope, is the scenario with the greatest impact. Its impacts are 21% superior to those of SC2-PV0.

Comparison of scenarios (optimistic end-of-life management)

Figure 101 shows climate change impacts for all scenarios, according to an optimistic end-of-life management.

As shown in the figure, a different approach at the end-of-life does not change the comparison between the scenarios. The contributions of the different avoided impacts and carbon storage will be further detailed in the next section.

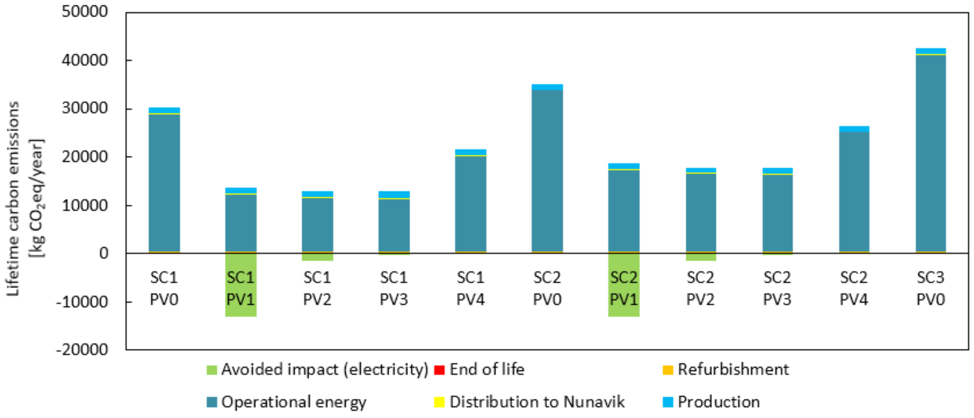

Figure 103. Contribution of life cycle stages to climate change for all scenarios.

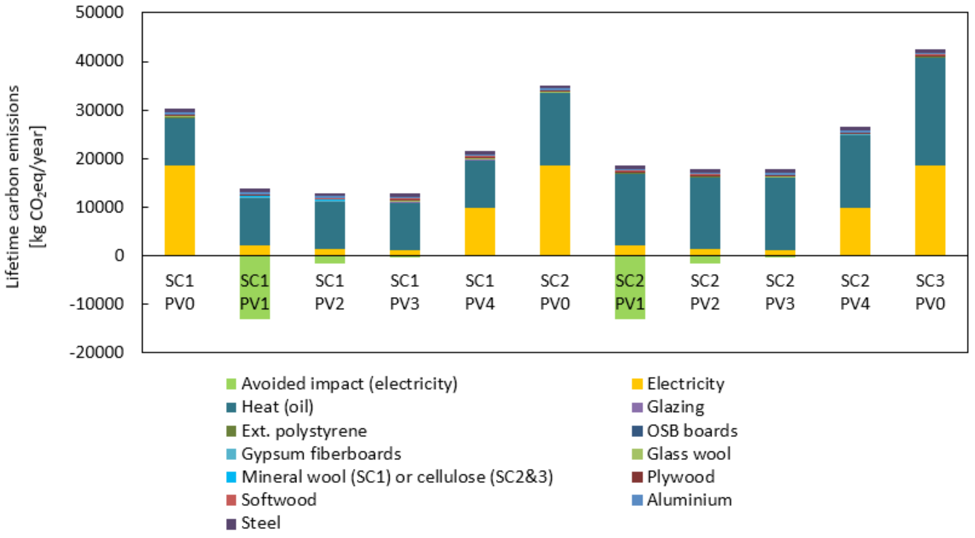

Figure 104. Contribution of materials and energy sources to climate change.

Carbon emissions by life cycle stages and by materials

Contribution analyses help to explain the differences observed previously between the scenarios. Since the sensitivity of the results to a change of end-of-life is weak (see Figure 101), the contribution analysis will be performed on the pessimistic scenario and the optimistic scenario will be assessed in a separate paragraph. Figure 103 shows that the main contributing stage is the energy consumption (heat + electricity) occurring during the case study building's operations. Depending on the scenario, it represents between 85% and 96% of the total impact (without accounting for avoided impact). The contribution of the production stage varies between 3% and 10%, while the other stages have a negligible impact. For example, the share of the end of life is 0.3% in average, with the maximum being 0.4% for SC1-PV3. A sensitivity analysis on the end-of-life scenarios seems therefore unnecessary at this point (without more precise data).

Owing to the preponderance of the operations, it is expected that the scenarios allowing a greater reduction of the operational energy consumption, i.e. scenarios SC1-PV1-3 have a greater potential for impact reductions. It should be noted that in the case of scenario SC1-PV1, the avoided impact is higher than the impact of the house's operational energy. The preponderance of the operations is mainly explained by the high carbon energy source used for the regional electricity mix and heat production (diesel). They also explain the high impact reduction potential of low carbon solutions such as solar energy.

Figure 104 presents a contribution analysis by materials (over their entire life cycle) and energy types. For Scenario 1, electricity consumption from the regional mix is the largest contributor (62% of the total impact without avoided impact), followed by heating (32%).

	Life cycle impact [kg CO_2eq/year]	Avoided impact (electricity) [kg CO_2eq/year]	Avoided impact (recycling) [kg CO_2eq/year]	Carbon storage [kg CO_2eq/ year]	Impact reduction due to electricity production	Impact reduction due to recycling	Impact reduction due to carbon storage
SC1-PV0	30,279		–736	–334	0.0	–2.4%	–1.1%
SC1-PV1	13,735	–13,020	–736	–334	–94.8%	–5.4%	–2.4%
SC1-PV2	12,962	–1,476	–736	–334	–11.4%	–5.7%	–2.6%
SC1-PV3	12,867	–63	–736	–334	–0.5%	–5.7%	–2.6%
SC1-PV4	21,594		–736	–334	0.0	–3.4%	–1.5%
SC2-PV0	35,142		–735	–315	0.0	–2.1%	–0.9%
SC2-PV1	18,598	–13,020	–735	–315	–70.0%	–4.0%	–1.7%
SC2-PV2	17,825	–1,476	–735	–315	–8.3%	–4.1%	–1.8%
SC2-PV3	17,730	–63	–735	–315	–0.4%	–4.1%	–1.8%
SC2-PV4	26,457		–735	–315	0.0	–2.8%	–1.2%
SC3-PV0	42,525		–735	–315	0.0	–1.7%	–0.7%

Table 34. Impact reduction potentials of solar electricity production, recycling and carbon storage.

When electricity is only produced from PV panels, as in scenarios SC1-PV1-3, the trend is reversed. Heating becomes the main source of impact (71%–75%) while the share of electricity consumption decreases to 10–15% of the total impact depending on the scenario. For the scenarios where heating needs are higher, as in scenarios SC2-PV1-3, the contribution of solar electricity becomes less than 10% on average.

The difference in the envelope between scenarios SC1 and SC2 does result in a decrease in material-related impact, of about 12%. However, the increase in energy-related impacts amounts to 52%, which explains why SC2 has a greater impact than SC1.

Finally, results show that materials are responsible for 6% of the impact on average (excluding avoided impact), with steel being the most contributing material. Considering only materials-related impacts, the share of steel amounts to 37% for scenarios SC1 and 42% for SC2 and SC3.

Influence of recycling benefits and carbon storage (optimistic scenarios)

Table 34 presents the influence of solar excess energy production, recycling benefits and carbon storage in terms of impact reduction for each scenario.

The highest potential of impact reduction for solar electricity production is consistent with previous observations that showed that energy consumption is the major contributor of the Nunavik house's carbon footprint owing to high carbon energy sources. Nevertheless, impact reduction due to materials' recycling, especially steel, is not negligible. For some scenarios like SC1-PV3 and SC2-PV3, recycling leads even to greater benefits than the substitution of regional electricity by solar panels. However, these results should be considered with caution because the assumptions related to the end-of-life scenarios are highly uncertain. Firstly, it is unlikely that steel, wood and aluminium products will be effectively 100% recycled at the end of life. Secondly, their recycling may not actually displace primary materials, whose displacement rates depend on actual markets. Finally, the benefits of carbon storage are almost negligible, except for scenarios SC1-PV2 and SC1-PV3, where they amount to –2.6%.

Discussion

This study shows that most of the efforts to decarbonize buildings in Nunavik should focus on net energy consumption. Energy consumption is estimated to be responsible for up to 94% of the carbon emissions of the case study building. There are two main explanations for this. First, harsh weather conditions drastically increase heating demand, so Arctic buildings in Canada usually have much higher energy demands than their counterpart in the southern regions. The other reason is that many Arctic communities rely on fossil fuel as their main energy source for micro-grids. In short, Arctic buildings consume a lot of energy that comes from carbon intensive sources. Because of this, the life-cycle impact of materials of a residential building is minimal compared to the one of its operation stage. The relatively small impact of materials signifies that it is preferable from a carbon standpoint to improve the envelope of a dwelling despite the additional embodied energy. We estimate that the prototype for northern housing produces 4,862 kgCO_2eq per year over its lifetime less than a similar building that would employ a less insulated envelope (reduction of 12%). This evidently does not mean that no care should be given towards the materials used for construction, but that one should not limit the addition of insulation materials in order to reduce embodied energy. On the community scale, another way to reduce the environmental impact of the operation stage would be to address the problem upstream by including cleaner energy (solar, wind, hydro or biomass) in the micro-grid mix. This analysis assumed that the energy mix of the local grids remains the same for the whole lifetime of the building. Exploiting energy from cleaner sources would directly reduce the lifetime carbon emissions of buildings.

In spite of the large carbon emissions of Arctic buildings, one of the studied scenarios was very close to yield zero-carbon results, with the avoided impact generated by PV panels being very close to the carbon emissions of the building. The net difference between life cycle impact and avoided impact for this scenario is 717 kgCO_2eq per year, which is a reduction of 98% compared to the life cycle impact of the prototype. This shows that an extensive use of solar energy can neutralize most of the environmental footprint of a building, even in the Arctic region. The impact of the materials related to the PV panels is minimal, again due to the enormous impact of energy use. However, it is important to mention that no energy storage technology was considered in the study, so it was assumed that the building could freely exchange electricity with the local micro-grid. This hypothesis can only work to a certain extent and cannot necessarily be extended over a whole community. The high monthly variability of the Sun as an energy source in the north represents a major challenge and short-term and long-term energy storage technologies such as batteries or seasonal heat storage are thus necessary to fully exploit the potential of solar energy.

Windows represent the weakest part of a building envelope and their production has a minimal carbon impact. From a carbon point of view, it would thus make sense to use highly efficient windows in order to reduce space heating demand. Efficient HVAC systems are also necessary as poor systems can cause energy waste and drastically inflate consumption as shown with the worst-case scenario. It should be noted that occupants represent a major player in the energy balance of a dwelling. With different occupant behaviour profiles provided to the numerical models, different levels of energy consumption could be obtained, which could strongly change the building lifetime emissions. Raising awareness to carbon footprint and energy performance, and adapting architecture and HVAC to occupants could therefore prove to be beneficial.

Cost analysis was not included in this study and could offer a different interpretation of the results presented in this study.

Japan

Introduction

In this analysis, the whole life cycle was divided into four stages: material manufacturing, repair, operation, and disposal. The evaluation period is 60 years. The calculation tool was MiLCA, a Japanese LCA calculation software based on the ISO standard. MiLCA can calculate CO_2 emissions from mass, volume, and price of the target object. In this analysis, the real estimation documents were used to identify materials and mass in the material-manufacturing stages. In the repair stage, the repair of the exterior walls, the windows and the roof were included in the calculation. In the disposal stage, two ways of disposal were calculated. In the first case, all materials were disposed as industrial waste. In the second case, wood was disposed as recycling material. The emissions during the process, such as transporting raw materials, machine-energy- consumption of manufacturing and demolition in factories and construction sites were left out because it was difficult to obtain accurate data. Table 35 shows the information in Case A and Case B. Both cases are real houses as shown in Figure 105. The construction system is a traditional Japanese wooden frame. The operation energy of each house was calculated as detached houses with four people. Table 36 shows the parameters of simulation cases in the energy consumption and disposal methods. The original energy sources for both houses were propane gas. Also, the present typical disposal method in the building field is to treat the material as industrial waste as shown in Table 36 We added Case (3) as a reuse case and Case (4) as a renewable energy case.

Figure 105. Photo of cases.

Results

Figure 106 shows the mass of the main materials. In the traditional Japanese wooden frame, the mass of wood material was almost half of the Finnish log case, whereas the amount of concrete and gypsum board is about 65 times and 10 times bigger than that in the Finnish log case because of the regulation for fire protection and earthquakes. CO_2 emissions in material selection are therefore higher. Also, the drying process for wood material emits more CO_2 than in Finland.

Figure 107 shows the CO_2 in the detached houses in Hokkaido. The CO_2 emissions without renewable energy sources are about 4,000 - 6,000 kg/m^2. Those with renewable sources are about 1,000 kg/m^2. The operations caused significant parts of CO_2 emission. The energy efficiency with thick insulation and high-performance ventilation is essential to reduce CO_2 in Hokkaido. Case B is more energy-efficient than Case A. But the CO_2 in case B is bigger than in case A. In Case A, the building is located in the rural area, also the building has the large south-facing window to get a passive solar effect to reduce heating energy. It reduced CO_2, especially of that produced during operation.

In this analysis, we implemented CO_2 analysis of relatively high-energy-efficiency houses built in Hokkaido. The parameters of the analysis were the usage of renewable energy and disposal methods in addition to the energy-efficiency. The Japanese government is promoting ZEB, and there are 341 houses registered as ZEH in Hokkaido (March 14, 2020). The UA value, average U value per wall area W/m^{2}K, should be below 0.25, depending on the size of the PV panel. Since the UA values of the houses examined this time is equivalent to the condition, ZEH could be achieved when enough PV panels were installed, but even in that case, zero and minus CO_2 could not be achieved for the following reasons.

- Traditional Japanese wood frame did not use enough wood like log-houses to achieve enough carbon fixation for negative carbon.

- Hokkaido people love large south windows for passive solar effect. However, large-area glass with multiple layers emits huge CO_2 in a production process.

- The traditional Japanese wood frame uses many metal members, concrete, and gypsum board due to their strength against earthquakes and safety against fire. Those materials emit huge CO_2 in the production process.

- Almost all processes for construction materials emit more CO_2 in Japan than in Europe. The change in electricity source from nuclear to coal-fire after Tohoku earthquake 2011 has influenced the situation. Also, lumber and construction for detached houses in Hokkaido are conducting in a small company. They have not improved the energy efficiency in their work.

	Case A	Case B
Floor area[㎡]	108.04	86.13
Number of floors	1	2
U-value[W/(㎡K)]	0.24	0.21
Energy	Propane gas	Propane gas
Ventilation	Mechanical ventilation	Mechanical ventilation
Structure	Wood frame	Wood frame
Rooftop	Galvalume	Galvalume
Interior wall surface	Plastic sheet Plaster	Plastic sheet
Facade	Galvalume	Wood
Insulation	Glass wool	Glass wool

Table 35. Information in Case A and Case B.

Case		Energy	Disposal method
Case A	(1)	Propane gas	Industrial waste
Case A	(2)	Propane gas	Wood chips
Case A	(3)	Propane gas	Reuse lumber
Case A	(4)	Wood chips, PV	Reuse lumber
Case B	(1)	Propane gas	Industrial waste
Case B	(2)	Propane gas	Wood§ chips
Case B	(3)	Propane gas	Reuse lumber
Case B	(4)	Wood chips, PV	Reuse lumber

Table 36. Parameter of analysis.

Recommendations

The following list summarizes the recommendations to policymakers emerging from this study to achieve zero CO_2 of the housing stock in Hokkaido:

- Timbering of parts other than the structure
- Wooden materials as insulation and exterior materials. Log construction, which uses more wood, can decrease carbon emissions. However, it is necessary to change the entire construction system, including the economy, based on the traditional Japanese wood frame. For this reason, a local government should support R&D for those materials.

REDUCING CO_2 EMISSIONS IN THE PRODUCTION OF BUILDING MATERIALS:

Compared to the European case for the production of various materials, the CO_2 emission of wood lumber is bigger in Hokkaido. It is necessary to use more renewable energy to achieve zero and minus CO_2. Governments need to give incentives to install new equipment and purchase more expensive electricity. Hokkaido is located in a cold region, but its latitude is low, so it is easy to get electricity with PV even in the winter season. The vertically installed PV, which can obtain power while snowfall season, is considered effective. Figure 108 on page 119 shows the comparison of PV output between the vertical case and the 45 deg. case. In the period from October to March, the vertical case produced more electricity.

REUSE OF COMPONENTS:

In this analysis, the wood recycled after disposal did not sufficiently decrease GHG because of the lack of wood materials in construction. However, in the traditional Japanese wood frame, many metal materials are used for the joints and exterior materials. Also, the foundation is constructed with much concrete. The recycling of those materials is effective in decreasing CO_2.

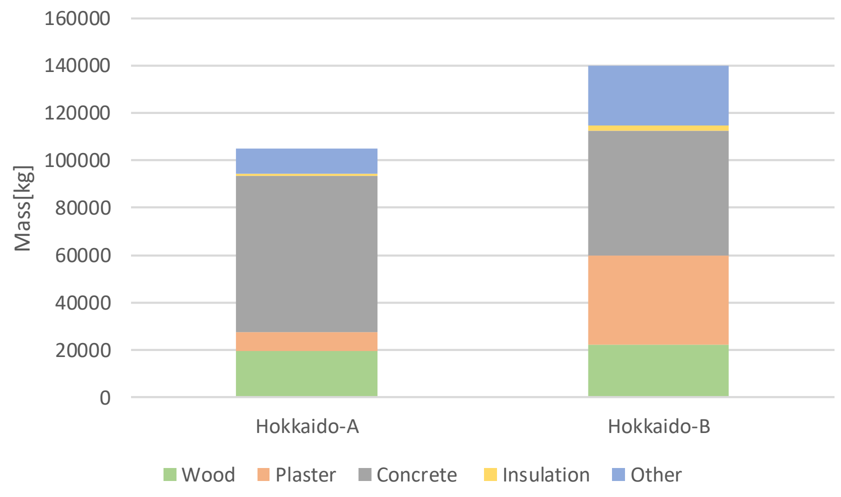

Figure 106. Mass of materials in Case A and Case B.

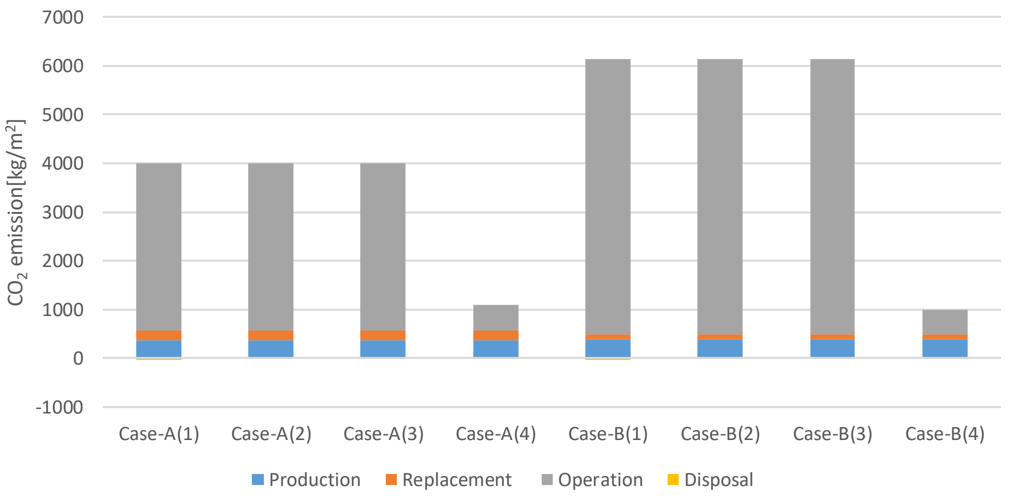

Figure 107. Results of GHG.

OPTIMIZATION OF WINDOW AREA:

In Hokkaido, people want to install large south windows for passive heating even in winter. However, the effect varies greatly depending on the region. Sufficient effects cannot be obtained in the western region. Also, the production of large-scale glass emits tremendous CO_2. Therefore, researchers should explore the complicated balance among passive solar effect, heat-loss, renewable energy to produce glazing system, lifetime, and CO_2. Figure 109 shows the CO_2 emission of the glazing system in the analysis. We can decrease the CO_2 in operation with renewable energy. Then a larger window emits larger CO_2.

PREFABRICATION:

Generally, a detached house in Hokkaido is constructed on-site. There are several disadvantages, such as waste management, available percentage of materials in the construction on-site. Prefabrication can reduce GHG. Also, it contributes to the shortage of human resources, which is currently the most serious problem in Japan. The local government should encourage the prefabrication of a construction company.

- Reducing energy consumption with traditional Japanese wood frame considering regional economic cycle.
- Insulation and air-tightness for the Japanese wooden frame have been developed in Hokkaido. Technicians are skillful for those techniques. Fortunately, Hokkaido has many forest resources. We should implement more R&D to decrease energy consumption considering the regional economic cycle and an economic ripple effect. The traditional and local materials-promoting techniques are essential to maintaining the local economy.

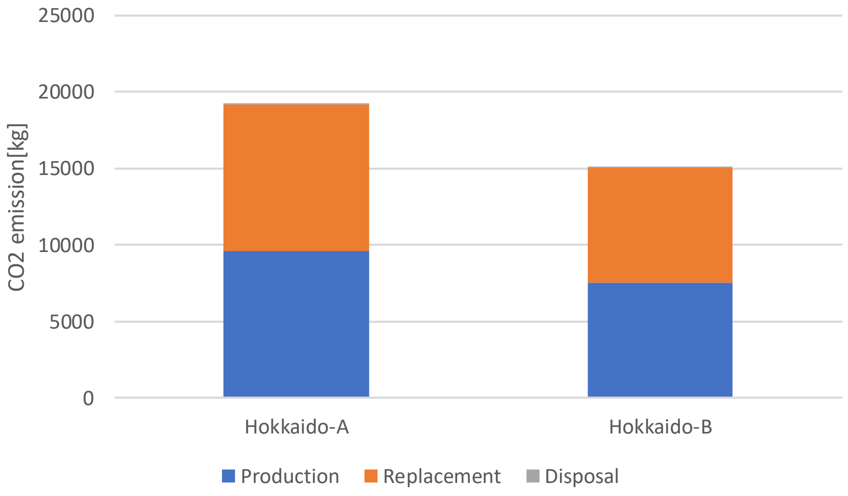

Figure 108. Comparison of PV output between the vertical case and the 45 deg. case.

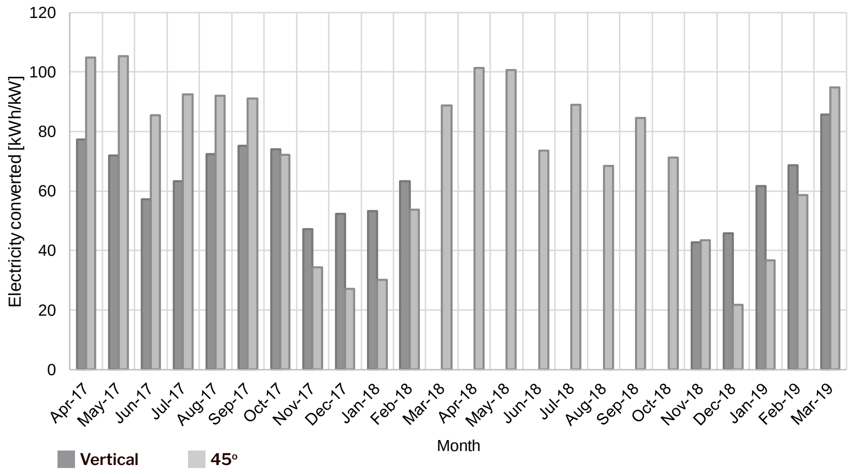

Figure 109. CO_2 emission of the glazing system in the analysis.

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The main goal of the project was to develop a sustainable and carbon-neutral building concept, based on traditional solutions, for the Arctic region. The significance of traditional and vernacular architecture lies in preserved examples of buildings that have had a service life of centuries. They form a source of knowledge to structural and material innovations that can be evaluated and used in modern buildings. The methodological novelty of the project was to unite architectural-historical and Life Cycle Assessment approaches to develop concepts that would be sustainable and carbon neutral at the same time.

One of the goals of this project was to learn from indigenous examples and knowledge, to be able to build homes for arctic conditions and people's needs. The historical examples show a great variety of indigenous architecture, but also similarities. Even though from the energy efficiency perspective the historical buildings may not fill the modern standards, there are things to learn for modern architecture - for example using light, local, renewable materials, designing buildings that are easily relocated, reused or deconstructed, and having rooms or spaces with different temperature for different purposes.

The examples of indigenous architecture presented in this report are mostly historical and not in use. The indigenous people in the studied areas mostly live in modern buildings. A good example of bringing the modern-day indigenous knowledge to practice is the Canadian case building, which was designed together with the Inuit and takes their special cultural needs into account. The studied case buildings had some ideas based on vernacular architecture, for example in the Finnish cases the use of local renewable material and half-heated spaces.

The study introduces traditional solutions for building in different Arctic districts in Finland, Canada and Japan. Potentials for low-carbon and carbon-neutral solutions were studied with the help of case studies. All case buildings were residential detached houses suitable for Arctic conditions, which fill the modern living standards.

The results between the countries' assessments have a big variation because of material types for construction and energy mixes used for building operation.

The carbon neutrality target was reached in the Finnish wooden case buildings, and the Canadian cases came very close with 98% reduction of GHG emissions in the case with high use of solar panels.

According to the Finnish assessment, the best suggested solution for Arctic conditions would be wood construction with the utilization of wind and geothermal energy for the building operation. In cases where wooden materials are reused in future construction projects, carbon emissions from wooden material incineration is not realized and biogenic carbon content, from wooden based materials, is therefore extended to the next building case.

It is important to note, that the benefits of the wood materials depend on what happens at the end of the building's lifecycle. As traditional log construction uses more wooden materials than 'MODIFIED', also more carbon embodied to the structures, therefore it serves well as a carbon storage during the building lifecycle. However, if the wood were to be incinerated, more forest growth would be needed to compensate these emissions. On the other hand, massive wooden structures are likely to be reused.

The extreme winter outdoor temperatures and possible vulnerability related to the reliance on the electricity supply set boundaries related to the modern HVAC systems in the Arctic Region. The HVAC systems should be designed to work in extreme e.g. -38 °C temperatures. The heat recovery heat exchangers of the mechanical ventilation system has to be equipped with the defrosting functionality to enable the operation and the fresh ventilation air for occupants in all conditions. The tap water system has to contain a functionality of draining the system for long absences without heating. The HVAC distribution systems has to be filled with circulation fluids enduring the extreme outdoor winter temperatures without frosting. Finally, the heating system has to contain a back-up functionality to cover the loss of grid power situations, typically a fireplace.

The research group found that wind energy would be the best renewable energy source in northern Finland. Wind energy is particularly advantageous because it can achieve reasonably balanced supply in relation to demand and because it causes a smaller carbon footprint than, for example, solar energy due to the large carbon-heavy batteries that the latter requires. It is reasonable to implement wind energy generation as a regional solution, which improves the cost-effectiveness of the electricity supplied. Wind power is suitable for both conventional (more energy-intensive) and modern construction, but for conventional construction more wind power is needed when low-carbon building is targeted. In the case studies examined, the energy need of a traditional house solution was about one and a half times that of a modified house.

Locations of new wind-power plants need careful consideration. Large-scale wind-power plants require environmental assessment, a process in which also impacts to indigenous peoples and local communities are examined and concerns heard. For example, in Norway an excessive wind power plant project was rejected in 2012 after engaging the indigenous peoples and local communities in the process[174]. Smaller plants can be built with local authorities' permission.

Wind-power can have an impact to the reindeer habitat selection. [175] By including indigenous peoples and local communities in decision-making processes where locating new power plants is decided upon, the possible negative impacts to local livelihoods could be minimized.

Solar energy has some disadvantages compared to wind energy. One disadvantage of the solar electricity is a slightly higher specific emissions per unit of energy produced by the current best photovoltaic technology compared to wind energy; another higher disadvantage is the seasonal imbalance between production and need.

Geothermal is an excellent solution for heat production in the Finnish Arctic when it uses electricity generated by wind power. On the basis of the case studies, the capacity required is typical (business as usual) in the case of the modified modern solution, but in traditional construction, the heating capacity is about twice as much as in modified construction.

The Finnish case shows, that an Arctic house can be dimensioned with renewable energy so that the hourly supply and demand meet more than half the time when wind power is used. In the studied case, wind power achieved on annual basis about 60% level of the simultaneous hourly energy demand versus supply with both traditional and modern house solutions.

In the Canadian context, replacing the use of diesel by renewable energy sources in the North will cut down carbon emissions. This includes both the electricity and the heating demands. Due to the harsh climate, investing in developing technologies that can facilitate the use of such sources (e.g., energy storage) might prove helpful.

In a full life cycle assessment, the end-of-life phase also needs to be included, although the scenarios are uncertain. In Canada, little information was found concerning "end-of-life" alternatives in the North. As carbon emissions from energy go down, it will become more and more relevant to study and develop low carbon end-of-life options.

The Finnish assessment considered alternatively, that wooden materials would be reused after end of their first life. This allows taking advantage from the biogenic carbon content of wooden materials as a carbon storage during the building service life and with the extension to the reuse case. It is assumed that wood is obtained from sustainable managed forests and then, normally a carbon neutrality approach could be applied.

For the Finnish "MODIFIED" case building it was calculated, that if the wood materials are burned at the end of the building's lifecycle, the carbon emissions from burning correspond to about 32 hectares of annual forest growth. In the case "TRADITIONAL" this number was 48 hectares. The assessment was based on annual growth rate per hectare of forest land in Northern Finland (2.7 m^3/ha/a).

However, as the end of life scenario for the wooden products was 'preparation for reuse', once used wooden product reused in the next case with the inclusion of it's embodied biogenic carbon content from the forest. Thus, whether carbon neutrality approach is realized or not depends on the next use case.

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Recommendations for policy-makers

When considering sustainability of buildings the focus should be on the full life cycle impacts. This is an overarching goal, the importance of which cannot be understated. This target should be met when pursuing the following objectives.

Optimal energy efficiency should be targeted in new buildings. Energy efficiency should not be pursued at the expense of potential service life or air quality.

If it is expected that the operational energy during a building's life cycle is produced by burning fossil fuels, improving energy efficiency is even more essential. However, it is important to examine the full life-cycle impacts of buildings and energy efficiency should be considered also as a question of long service life, recoverability and reusability.

Renewable energy should be included in the micro-grid mix. The decision-maker of an individual building project can use renewable energy (with PV panels and collectors, pumps), which can have a major role in the carbon footprint of this building. Solar/PV collectors can be a good source of energy but the solar conditions they require are not available all year round in the Arctic. Also, investments in cleaner energy regionally would have a major impact on the GHG emissions (wind, hydro). It is important that new energy production is planned with respect to indigenous peoples and local communities and their needs.

Low-carbon materials, such as wood from sustainably grown forests, should be preferred. Wood is the only material that can compensate the emissions from construction and use. However, to reach the full benefit, the wooden materials should not be burned in the end of the building's life cycle, but reused as much as possible.

The buildings should be designed to enable deconstruction (Design-for-deconstruction), reassembling and reuse. The building can be designed in a way, that the whole building could be moved to another location. This is possible for example in traditional log construction, such as the first Finnish case building. Considering the melting permafrost, relocating buildings might be an important issue to consider in Arctic areas in the future. The buildings and the building parts should also be designed for a long lifecycle, so that reassembling and reuse is possible.

The buildings should be designed for climate resilience. This may include low technology use, maintenance with simple tools use and easily adjustable dwelling operation to unexpected, rapid and extreme all-weather, all-seasons changes.

Occupants' needs and profiles should be considered in the design and operation of the building. Different studies showed an important difference between the preconstruction energy consumption estimates and the measured performance, often due to wrong assumptions on how occupants would use the building. Better considering the occupants' needs and profiles in the design and operation of the building, and raising occupants' awareness regarding the environmental impact of energy use in buildings would certainly help to reduce energy consumption. Involving the inhabitants (for example Inuit in the Canadian case) in the design process of houses, conducting post-occupancy to understand how they feel about topics such as energy and buildings, and monitoring real buildings could be beneficial for this.

Suggestions for further research

The Zero Arctic project opened discussion on carbon neutral and sustainable arctic building. The focus was on ecological aspects, with respect to cultural values. However, to also cover the economic and social pillars of sustainable development, further research would be needed. Especially building life cycle cost analysis (LCC) for case buildings with different solutions would provide useful information.

The Finnish study group found Canada's approach to planning process inspiring. The Finnish case buildings were designed for northern conditions, but not especially for the Sámi lifestyle, although comments were gathered. This further study would involve full Sami collaboration and integrated climate resilience design - covering detail design, construction, habitation and monitoring of one or more dwellings. Deep listening of recent Sámi experience could create more radical concepts to shake our way of seeing good living.

It is worth highlighting, that the regions that were included in the study do not represent all Arctic regions. Therefore it would be of great value to see similar studies conducted in other Arctic regions as well.

Contributions

Zero Arctic project (2018–2020) works under the Arctic Council and its Sustainable Development Working Group.

The project was led by Ministry of Environment of Finland, together with Crown-Indigenous Relations and Northern Affairs Canada. The project was supervised by Ministry of Environment senior specialist, PhD Matti Kuittinen with support and ideas from Senior Arctic Official Henna Haapala and coordinated by Eeva Huttunen.

The findings and material of the three international teams were put together and edited by Eeva Huttunen, Marko Huttunen, Panu Savolainen, Frans Saraste and Sirje Vares in dialogue with the project teams of Canada and Japan.

Executive Summary, Introduction and *Conclusion* chapters were written by the Finnish project team in dialogue with the project teams of Canada and Japan.

The graphic design of the cover and title pages is by Susan Novotny while the rest of the graphic design of the report is by Johannes Nieminen. The layout and illustrations are by Frans Saraste with layout help from Juulia Mikkola.

The final report was circulated for comments in SDWG Member states, Observers and Permanent Participants. All given comments were discussed with the project group and the report edited. Language checks were provided by Saana Rusi, Juulia Mikkola and Katherine O'Leary.

Finland

The project coordination and research in Finland was funded by the Ministry of Foreign Affairs of Finland.

The solid drafts of chapters 2, 3 and 5 were written by Marko Huttunen and PhD. Panu Savolainen from Livady Architects.

The research and solid draft of chapter 4 was conducted by M.Sc. (Tech.) Sirje Vares, M.Sc. (Tech.) Jari Shemeikka and PhD Tarja Häkkinen from VTT.

3D-modeling of vernacular dwellings were made by Laura Zubillaga. Visualisations and illustrations were made by Frans Saraste.

The case-study houses were designed in Livady by architects Marko Huttunen and Laura Zubillaga with help from Frans Saraste.

Livady consulted architect Neil Winder on matters of climate resilience.

Life-cycle assessments and energy simulations were conducted by Sirje Vares, Jari Shemeikka and PhD Tarja Häkkinen from VTT.

The research team received support and ideas from Päivi Magga and Darja Heikkilä from The Sámi museum Siida. Permission to use the cultural knowledge of the Sámi people was granted by the Sámi Parliament on December 11, 2018. The Sámi parliament represents the Sámi people in national and international affairs in accordance with § 6. The Sámi Parliament gave useful comments for the report draft.

Canada

The staff from Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC), in particular Fadi Cherri and Doug Klassen, helped to the elaboration of this report by providing the overall outline, as well as a solid draft for Chapters 2 and 3.

Professor Louis Gosselin, P. Eng., Ph.D. (Université Laval) coordinated this work and participated to the writing and revision of most sections.

Dr. Jean Rouleau, Jr. Eng., Ph.D. (Université Laval) prepared the maps and text of Chapter 3. He developed and ran the energy models of Chapter 4, and participated to the writing of that case study. He also helped with assembling and revising the document.

Dr. Audrey Tanguy, Ph.D. (Université de Sherbrooke) performed the life-cycle analysis of Chapter 4 and participated to writing this chapter with the help of Professor Ben Amor, P. Eng., Ph.D. (Université de Sherbrooke).

Paméla Peer-Corriveau (Université Laval) helped collecting data and information for Chapter 2.

Dr. Noémie Chagnon-Lessard, Jr. Eng., Ph.D. (Université Laval) helped revising the document and provided some figures for Chapter 2.

Pierre-Olivier Demeule and Professors Geneviève Vachon, MOAQ, Ph.D., Myriam Blais, MOAQ, Ph.D. and Geneviève Cloutier, Urb., Ph.D. (all from Université Laval) provided pages 48-49 and helped to complete Chapter 1 with information relative to Nunavik. The images on pages 48-49 was taken by P.-O. Demeule in Salluit, Nunavik.

All questions about Canadian part of the report could be addressed to Professor Louis Gosselin (Louis.Gosselin@gmc.ulaval.ca).

DISCLAIMER

Even with all the care that we devoted to provide accurate data and information, and despite of the verifications and proofreading that we did, it is possible that mistakes or inaccuracies have remained in the text. However, to the best of our knowledge, the document reflects the currently available information.

The document is not meant to be exhaustive, in particular regarding vernacular architecture, the historical evolution of housing, the best design practices in each region and territory, and the examples of houses presented in the report. We believe, though, that the report provides an accurate overview on these topics.

Japan

The project coordination and research in Hokkaido were partially funded by J-ARC-net of Arctic Research Center in Hokkaido Univ. The project was lead by associate professor Mori Taro and the Laboratory of Building Environment, Hokkaido University.

Abe Yuhei (Northern Regional Building Research Institute), Yamamoto Ako (Yamamoto Ako architecture studio), and Inoue Nozomu (Indi co. ltd) supported us on the topic of History of R&D of a residential building in Hokkaido. Ohashi Yoshinori (Forests Products Research Institute) helped to write the section on Wood Architecture in Hokkaido. Life-cycle assessments and energy simulations were conducted by Ooi Marina and Hayashi Taisuke (Graduate student of Hokkaido Univ.) Data for the analysis was provided by Yamamoto Ako (Yamamoto Ako Architect studio) and Ogura Hiromasa (sa-design office). Construction of Chise and the research was financially supported by Grants-in-Aid for Scientific Research. Principal investigator is professor Nishizawa Takeo (Kushiro National College of Technology).

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