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Life cycle energy use and carbon emission of a modern single-family residential building in Nepal

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ABSTRACT

The rapid urbanization and rural-urban migration trends have led to an increase in building construction activities, shifting from traditional practices to modern concrete structures. However, this transition has imposed significant environmental pressures, including heightened resource and energy demands, resulting in increased emissions. To gauge the environmental impact of construction, a thorough examination of each phase is crucial. This study used the Life Cycle Assessment (LCA) tool, based on ISO 14040:2006, ISO 14044:2006, and EN 15978:2011, to evaluate the carbon dioxide equivalent (CO_2-eq) emissions throughout the complete life cycle of a modern single-family residential building. The findings reveal a total energy use of 6411.33 MJ per square meter and emissions of 718.35 kg CO_2-eq per square meter over the building's lifespan of 50 years. Notably, the production of building materials and the construction phase contribute to the highest percentage (60.29%) of the total life cycle emissions owing to 49.51% of energy use. In contrast, emissions during the operational phase are relatively lower, attributed to increased electricity usage for cooking and minimal energy consumption for heating and cooling. Additionally, the study suggests that achieving complete electricity sufficiency within the country could reduce building emissions by 39.30%, as fossil fuel-based imports from India would be replaced with cleaner hydroelectricity.

1. Introduction

Climate change is one of the most significant environmental challenges of the twenty-first century and poses a very high risk for countries like Nepal. Nepal is ranked tenth most climate change-affected country in the world by the Long-Term Climate Risk Index (Eckstein et al., 2021), and 80% of the people are susceptible to the risk of climate-induced hazards like flood, landslide, heat stress, and drought (MoHA., 2018). Floods and landslides are the most frequent hazards in Nepal and the number of events has doubled in recent years (World Bank, 2022). The temperature in the Indian subcontinent is predicted to rise between 3.5 and 5.5 °C by 2100 and in the Tibetan Plateau by 2.5 °C by 2050 and 5 °C by 2100 (ICIMOD, 2009). A recent study by the World Bank and Asian Development Bank shows that Nepal will face a loss of 2.2% of its annual gross domestic product due to climate change by 2050 (WBG and ADB, 2021). Rapid and haphazard urbanization makes people more vulnerable to the impact of Climate change (UNFCCC, 2017).

More than half the world's population today live in cities (UNFCCC, 2017) and by 2050, 70% of the world's population is forecasted to live in cities, making cities critical to achieving Sustainable Development Goals (GRI, UN Global Compact and WBCSD, 2015). Urban areas account for up to 80% of energy consumption and 75% of global waste and carbon emissions (UNEP, 2022). In 2021, 66.08% of Nepal's total population resides in urban areas, accounting for 67.19% of the total buildings in the country (CBS, 2021). Buildings utilize a significant quantity of resources and energy emitting large amounts of emissions to the environment which contributes to climate change. The building construction and operation accounts for 35% of global energy use, are responsible for

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nearly 40% of energy-related carbon dioxide equivalent emissions (Nwodo and Anumba, 2019), 15% of the water use, and generates 25% of all wastes generated (Ramesh et al., 2010). Fossil fuels contribute about 80% of the total primary energy required for buildings which contributes to two-thirds of greenhouse gas (GHG) emissions in the world (Petrovic et al., 2019).

To limit the changing climatic conditions and overcome the impact of climate change, efficient and effective design and selection of construction materials and practices are necessary. Efficient and effective building construction can lead to a reduction of the total energy consumption of the building by 42%, a reduction of GHG emissions by 35%, a reduction of the use of natural resources by 50%, and a reduction of water use by 30% (Herczeg et al., 2014).

Estimation and calculation of the carbon emission of a building is a complex process. The fundamental processes of carbon emission quantification are the process analysis method, the input-output analysis method, and the hybrid method (Liu et al., 2020). The process analysis method uses input as materials/energy and outputs as emissions/waste for each process of the whole lifecycle and is widely used in engineering and construction technologies; the input-output method is used for quantifying the direct and indirect emission of large supply chains using the geographical area for system boundary; and hybrid method uses the combined advantages of both methods to get the comprehensive insight of emissions from complete supply chain (Fenner et al., 2018). Life Cycle Assessment (LCA) is widely used across the world to analyse the energy demand and carbon emission from buildings with different design alternatives considering life cycle span ranging from 50 years to 120 years based on local context (Rasmussen and Birgisdóttir, 2016; Petrovic et al., 2019; Frischknecht et al., 2020).

In the last decade building construction in Nepal increased by 22.82% due to increasing urbanization, rural-urban migration, and post-earthquake reconstruction after the Nepal earthquake in 2015 (NSO, 2023). With the increasing number of building constructions, the construction sector in Nepal is increasingly using composite materials, modern design, and foreign technology replacing traditional vernacular architecture and sustainable building construction materials (Rijal, 2012). From 2011 to 2021, buildings with cement-bonded brick/stone walls and buildings with RCC roofs reached 52.17% and 37.76% from 28.74% and 22.48% respectively (CBS, 2012; NSO, 2023). The National Planning Commission reported that the Nepal earthquake in 2015 completely damaged 498,852 houses (NPC, 2015) which were replaced by cement concrete buildings during reconstruction. LCA of the building in Norway shows that an increase in the use of wood in the building reduced the energy requirement of the building leading to GHG reductions (Moschetti et al., 2019). The increasing use of composite construction materials and imported technology along with the long transportation distance of these materials is changing the environmental impact and emission to the environment. However, there are limited studies to date in Nepal on the assessment of environmental emissions of the buildings throughout their life cycle.

This shows a research gap in the nexus of building, energy, and environment in the context of Nepal and raises the question: What is the energy use and emission in each stage of the Nepalese building life cycle? How do different building components influence energy use and emission? This research study investigates the energy use and carbon emission of reinforced concrete single-family residential buildings in Nepal and analyses the interaction of components and materials on carbon emission. This study shall serve as a guideline for planners, designers, and practitioners in quantifying emissions from the buildings and moving towards cleaner development for achieving Sustainable Development Goals (SDGs). The outcome shall also guide policymakers in the prioritization and development of policy, standards, and codes for achieving the target of a carbon-neutral nation by 2045.

2. Methodology

LCA has been widely used across the world to assess the impact of buildings in each stage of their life cycle. The study used simplified LCA aproach following a cradle-grave approach with a detailed study on energy use and carbon emission from all four stages of the building life cycle as prescribed by ISO 14040:2006 (shown in Fig. 1), ISO 14044:2006 and EN 15978:2011 (shown in Fig. 2). The LCA methodology framework consists of four phases: Goal and Scope definition, Inventory analysis, Impact assessment, and Interpretation for application as shown in Fig. 1. The study was done based on the system boundary of all four stages of the building life cycle. The four stages of the buildings are further subcategorized into 16 sub-stages as defined by EN 15978:2011 for detailed evaluation (Refer to Figure S1 of Supplementary file) and 12 sub-stages considered in this study are shown in Fig. 2.

Different studies conducted in different parts of the world consider different substages of the building life cycle based on the local context and resources. The comparative study conducted on 13 countries considered different substages of the building life cycle as defined on EN15978 is presented in Table 1, consideration of these different subcategories of the life cycle is based on the local scenario and limitation (Frischknecht et al., 2020). So, this study considered sub-stages A1-A3 to account for embodied energy and carbon from material production, A4 for transportation, and A5 for the construction process of the buildings. The energy use in production, transportation, and construction is adopted from the database of Eco-invent Version 3.8 (2021). The materials inventory is derived from a design drawing and bill of quantity of the case study residential building, which is presented in Fig. 3, and information from field and civil work norms of the government of Nepal (MoUD, 2023).

The operational phase of the buildings substages B6 is considered while the energy use and its associated emission for pumping of the water is accounted for in B6. The energy usage as specified in B6 is accounted for based on the average electricity bill and energy used for cooking is accounted for based on the field data. Nepal is the least-developed country with energy poverty (Thapa et al., 2023) and there is limited use of air conditioners, and occasional use of fans and heaters is accounted for in electricity bills considered in B6. Emissions from energy use are derived based on IPCC Guidelines, Vol 2 (IPCC, 2006). Information on repair, replacement, and refurbishment is not available so it is not accounted for in the study. The energy use of each fuel is accounted for in the form of megajoules (MJ) while the electricity is accounted for in kWh and then converted to MJ for uniformity. The specific energy consumption per square meter is determined with an account of the total habitat area as defined in the functional unit.

The end-of-life stage of the buildings, substages C1, C2, and C4 was accounted for in the study which includes the deconstruction/demolition, transportation, and disposal of the materials. The demolition of the building is done manually in Nepal by human laborers using traditional tools and concrete breakers. The substage C3 is not accounted for as most of the demolished waste like windows, doors, bricks, and wood are directly reused in building construction itself, and other waste is used in backfilling of construction sites or road potholes without any processing (Khanal et al., 2021).

2.1. Goal and scope definitions

The defined goal of this research study is to determine the life cycle energy use and potential carbon dioxide equivalent (CO_2-eq) emission of the typical modern two-and-a-half-story residential building in Nepal. The study assessed the embodied energy of the building from the production and transportation of the construction material, construction process, and operation of the buildings along with demolition and transportation of the building material at the end-of-life stage. The construction material supply stage embraces the amount of energy

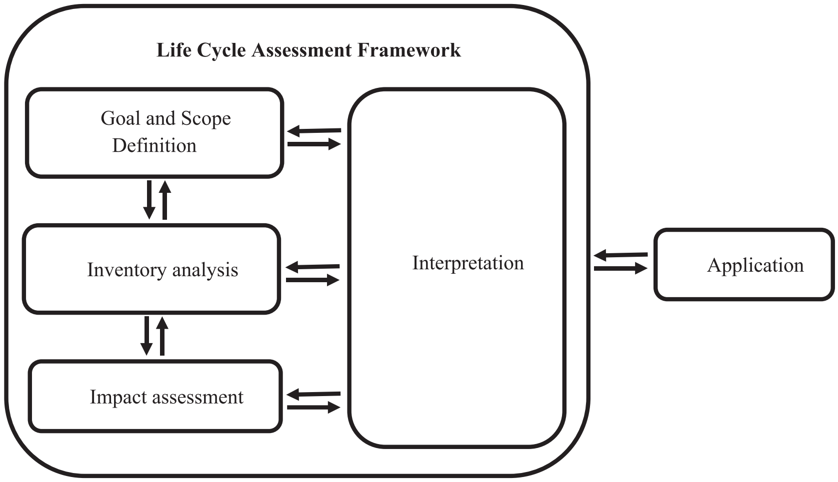

Fig. 1. Life Cycle Assessment process framework (ISO 14040, 2006).

Production Stage			Construction Stage		Operation Stage				End of Life stage		
A1	A2	A3	A4	A5	B1	B2	B6	B7	C1	C2	C4
Raw Materials Supply	Transport	Manufacturing	Transport to building site	Construction and Installation	Use / Application	Maintenance	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Disposal

Fig. 2. Life cycle stages of buildings adopted from EN 15978 and modified.

Table 1
Overview of the life cycle stages considered in the studies (Frischknecht et al., 2020).

Life cycle stage	Production	Construction	Operation						End of Life stage			
Country of Study	A1- A3	A4- A5	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
Austria (AT)	X	X			X		X			X	X	X
Brazil (BR)	X	X			X		X		X	X		
Canada (CA)	X	X			X		X		X	X	X	X
China (CN)	X				X							X
Czech Republic (CZ)	X				X		X					
Germany (DE)	X				X		X				X	X
Denmark (DK)	X				X		X				X	X
Spain (ES)	X	X	X	X	X	X	X	X	X	X	X	X
France (FR)	X	X			X		X	X		X	X	
Hungary (HU)	X	X		X	X		X			X	X	X
Italy (IT)	X						X					
Norway (NO)	X				X		X				X	X
New Zealand (NZ)	X	X	X		X		X	X	X	X	X	X
Portugal (PT)	X											
Sweden (SE)	X	X										
United Kingdom (UK)	X	X			X		X		X	X	X	X
United States (US)	X	X	X		X		X		X	X	X	X

X in the table signifies the life cycle substages considered in the respective studies.

utilized and greenhouse gas emissions from the mining, processing, production, and transportation to the construction site. The building construction stage includes the CO_2-eq emission due to the construction process, from site clearance to complete construction of the building and installation of the fixture. The operation stage of the building is considered for the life span of 50 years and the energy consumption pattern is considered the same throughout the operation period of the building. As most of the demolition materials from the building are reused in the construction work itself, so, only the demolition activity, transportation, and disposal of the demolished materials are considered in the assessment.

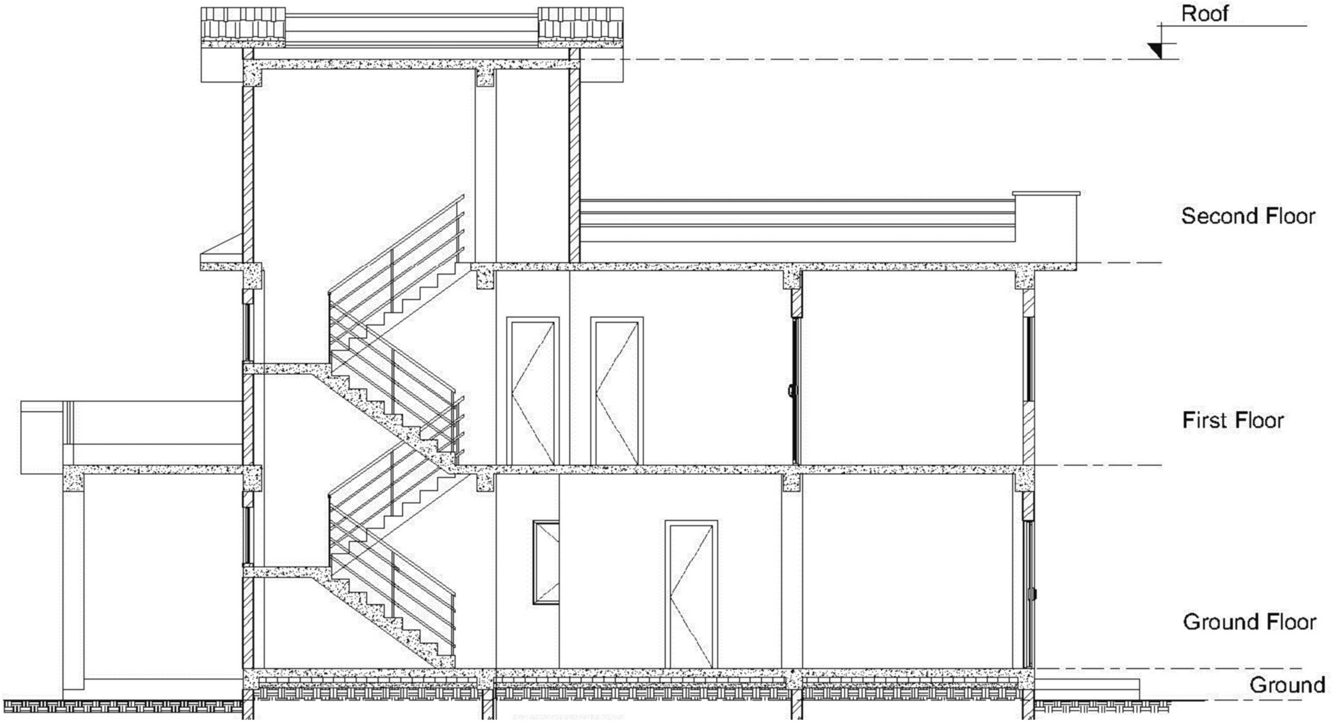

Fig. 3. Elevations, floor plan, and section drawing of the building.

2.2. Functional unit

The functional unit selected is 1.00 m^2 of the habitable surface of a two-and-a-half-story residential building typical for a family of five in Nepal. The functional unit provides the applicable and multipliable value for the buildings to which the input and output data are normalized.

2.3. Case study - reinforced concrete residential house

In Nepal, 71.70% of the buildings are residential buildings and 52.20% of the buildings are made of cement concrete (NSO, 2023). Therefore, the LCA of a reinforcement concrete structure single-family residential building is conducted. The building is a frame structure of reinforced concrete with brick masonry walls in cement mortar and has a gross area of 230.10 square meters. The floor and roof of the building are reinforced concrete. The floors are either finished in cement punning or porcelain tiles. The doors are made from solid wood and the windows of unplasticized polyvinyl chloride (uPVC) frame with single-glazed glass. The iron is used for the staircase bar, stairs for the terrace, and the main external boundary gate. The drawing of the floor plan, elevation, and section of the building is presented in Fig. 3.

2.4. Inventory analysis

The inventory of the building was developed with the compilation and evaluation of the inputs, outputs, and potential environmental impacts of all the major materials used throughout its life cycle based on the set boundary as prescribed on IS/ISO 14044:2006. The life cycle inventory accounts quantity of each material used and the output from the construction process and operation of the building. The inputs in terms of the materials and embodied energy were obtained from the detailed bill of quantity of the building based on the design and detailed drawings collected from the field (some presented in Fig. 3), and information from field and civil work norms of the government of Nepal (MoUD, 2023). The emission and energy use data are adopted from the Ecoinvent Version 3.8 (2021) database while operational energy data is obtained from the case study building's operation. Electricity is primarily used for the operation of the tools and equipment used in construction activities and end-use applications. Diesel is used for site clearance and excavation works, transportation of materials, and operation of concrete mixing machine during the construction stage. Emission of CO_2-eq from electricity and combustion of fossil fuels during material production, transportation, construction process, and operation stage of the building were accounted. Most of these materials production takes place in Nepal while some materials are imported from India. For the materials that are manufactured in Nepal, Nepal's electricity mix dataset was used, and for the materials that are imported from India, the Indian Electricity mix was used.

The energy mix of the electricity for Nepal is based on the portion of the electricity produced from hydropower in Nepal and energy imported from India. Table 2 summarizes the electricity use and calculated emission factor for the energy mix of Nepal for the fiscal year (FY) 2021/22. The total electricity consumed in the fiscal year 2021/22 was 8823 Giga Watt hours (GWh) with transmission and distribution loss of the electricity was 17.18%. (NEA, 2022). The average CO_2-eq emission of the energy mix of the electricity of Nepal is 483.97 gCO_2-eq /kWh (Table 2).

Table 2
Energy sources and emissions of the energy mix of Nepal for the fiscal year 2021/22.

Energy Source	Energy consumption FY 2021/22 (NEA, 2022)	Emission factor (gCO_2-eq /kWh)	Emission factor with losses (gCO_2-eq/kWh)	References
India	1543	2100	2460.78	(cBalance Solutions, 2011)
Nepal	7280	55.42	64.98	(Varun and Prakash, 2012)
Total	8823		483.97	

2.5. Impact assessment

Life cycle impact assessment derives the life cycle inventory into indicators to present the environmental impact of the building components from the production and construction stage, operation stage, and end-of-life stage of the buildings. The assessment process involved the calculation of the total energy embodied in each process and then converting this embodied energy to a CO_2-eq (Biswas, 2014) using Nepal's energy mix. The impact assessment interpreted the result obtained from the inventory analysis. The Eco-invent Version 3.8 (2021) database is used to determine the energy use and associated carbon emissions in the material production, construction process, transportation, and operation of the building. For the relevance of the results in the Nepalese context, available data were localized through contextualizing with a local scenario as per Nepal's energy mix and comprehensive inclusion of transportation. The supply chain of the construction materials was incorporated to assess the GHG emission arising from the transportation of the construction materials from production plants to the construction site. For delivery of the larger construction materials, a mini truck of capacity nine tonnes (t) was taken.

3. Result and discussions

The buildings' life cycle analysis shows that the material production and construction phase governs the total energy use and CO_2-eq emission of the reinforced concrete residential buildings in Nepal. Table 3 summarises the amount of construction materials used for the construction of the building, energy consumption in each material production, construction process, transportation, household appliances in operation, and end-use application.

3.1. Embodied energy of residential buildings

The LCA for the total embodied energy of the building with a total life of 50 years duration shows that the material production and construction stage of the building governs the total energy use of the building. The total life cycle energy of the accessed building is 1475.25 Gigajoules (GJ), which is 6.41 GJ per square meter of the building. The LCA result shows that the building consumes 49.25% of the total energy during the construction material production and construction stage followed by the operation stage which consumes 46.78% of the total building life cycle energy. The end-of-use stage only consumes 3.11% of the total energy mainly from the demolition of the building and the transportation of the demolished waste. The major source of energy for construction material production is coal followed by electricity while the major of energy for the operation stage and end-of-life stage is electricity. The energy used in the building from different sources is presented in Fig. 4.

The specific energy consumption of the building for construction material production and construction process is 3212.61 MJ per square meter. The specific energy consumption during the operation of the building is 2999.30 per square meter (59.99 MJ per square meter per year) which accounts for the energy use for building operations like operation of machinery and tools, fuel for cooking, heating, and cooling. This was obtained from the monthly electricity consumption and fuel used inventory from the field. The demolition and transportation of the building at the end-of-life stage of the building accounts for only 199.44 Megajoules (MJ) of energy per square meter of the building floor area.

The study shows that the major source of cumulative energy use of the building is hydroelectricity followed by coal as potrated in Fig. 5. The major source of energy for the material production and construction stage is coal followed by electricity while the major source of energy in the operation stage of the building is hydroelectricity and liquefied

Table 3
Data on material quantity utilized for building.

SN	Material Required	Units	Quantity	Transport (km)	Embodied energy (MJ)	Total (kgCO2-eq)
Material Production and Construction Stage						
1	Water	lit	31,618	10	56.91	9.79
2	Brick	Nos	55,941	27	242,737.12	29,376.49
3	Sand	m^3	134	68	10,894.59	1081.43
4	Cement Portland	kg	70,289	263	260,609.10	31,531.58
5	White Cement	kg	42	263	5.70	0.94
6	Aggregate	m^3	93	68	111,336.63	17,103.24
7	Wood	m^3	9	215	181.04	29.34
8	Bamboo	kg	1480	215		0.57
9	Reinforced Iron	kg	14,286	263	49,995.29	7404.54
10	Brass door lock	kg	20	263	141.58	14.88
11	Porcelain Tiles	m^2	187	1410	21,563.14	8142.28
12	16 mm marble	m^2	62	1450	6275.81	2369.78
13	uPVC Door	m^2	42	200	10.95	1.74
14	uPVC Windows	m^2	42	250	11.14	1.77
15	Bulb	No	52	250	–	0.02
16	Copper wire	kg	92	20	4325.47	700.99
17	Switch	kg	13	800	883.35	143.17
18	Taps	kg	8	200	56.63	5.95
19	Wash basin	No	4	1300	334.08	126.30
20	Water closet	No	4	1300	348.10	131.60
21	Kitchen sink		1	800	294.00	47.65
22	Mixture	hr.	52		7156.09	706.14
23	Vibrator	hr.	27		4505.41	730.15
24	Transportation				17,496.83	45.08
Operation Phase					690,135.84	65,372.2
1	Electricity				280,800.00	45,506.53
2	Liquid Petroleum Gas				409,355.84	19,865.66
End of life Stage					45,891.56	259.48
1	Demolition and management				32,032.86	224.03
2	Transportation				13,858.70	35.45
Total Floor area		m^2	230		1475,246.38	165,292.06
Per unit floor area (1 m^2)					6411.33	718.35

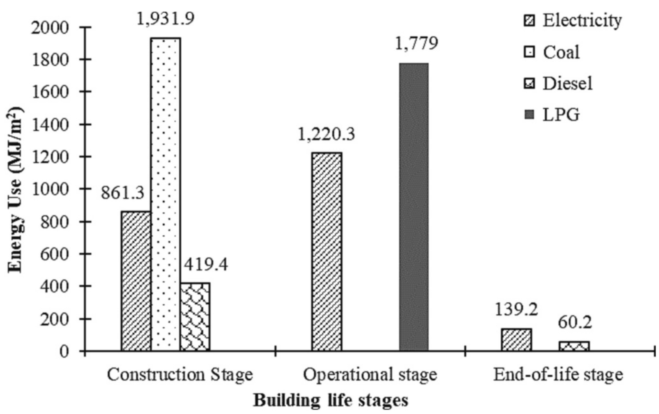

Fig. 4. Embodied energy of the building at the different stages as per energy source.

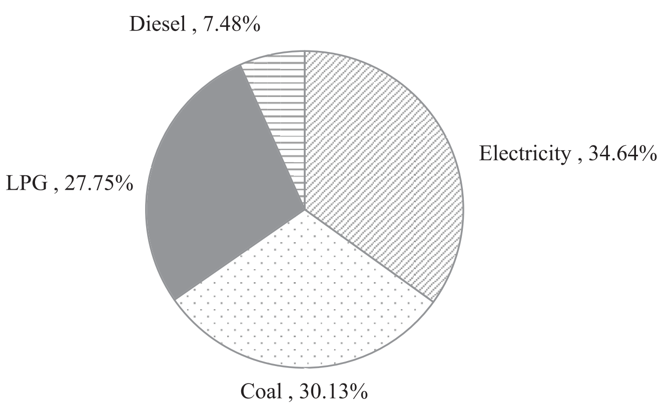

Fig. 5. Source of energy (MJ) for the total life cycle of the building.

petroleum gas (LPG). The building uses 34.64% of the total embodied energy from electricity of which 54.95% is during the operational stage, 38.78% during the material production and construction stage, and 6.27% at the end-of-stage for demolition of the building. The building utilizes 30.13% of its total energy from coal and is utilized during the material production stage (mainly brick and cement production). LPG is a major source of energy for cooking and it accounts for 27.99% of the total energy, all of it is utilized in the operational stage of the buildings. Consumption of diesel is mainly on the production of brick, sand, cement, and aggregate and the transportation of the materials to the construction site. The major source of life cycle energy use of building is presented in Fig. 5.

3.2. Carbon emission

The carbon dioxide equivalence emission of the life cycle stages of the case study building with a life span of 50 years is 165.29 t CO_2-eq. The calculated CO_2-eq of the building per unit floor area is 718.35 kg per square meter, and which is 14.37 kg CO_2 equivalent per square meter per year. The major share of the emission from the building is during the material production and construction stage as it emits 60.29% of the total life cycle emission followed by 39.55% in the operational stage. The LCA result showing the emission potential in different life cycle stages is presented in Table 4.

The major source of emission in the material production and construction stage is coal while in the operational stage, it is electricity. The total emission from different sources of energy for the building shows that 50.82% of the total emission is from electricity followed by 32.40% from coal. LPG contributes 12.02% of the total emission from the building which is used for cooking during the operational stage. The complete replacement of the electricity imported from India by the electricity generated from the hydropower of Nepal shall reduce the emission of CO_2-eq emission in the operational stage by 61.85% and CO_2-eq emission in the total life cycle stage of the buildings by 39.30% as emission from electricity generated from Nepal is 64.98 gCO_2-eq/kWh and emission from electricity imported is 2460.78 gCO_2-eq/kWh. The emission from a different source of energy in each stage of the building life cycle is presented in Fig. 6.

Table 4
LCA results showing the greenhouse gas emission potential from different life cycle stages of a residential building.

Life cycle stages	GHG Emission potential			
	kg CO_2-eq	kg CO_2-eq/m^2	kg CO_2-eq /m^2/y	Total (%)
Material Production and Construction Stage	99,660.38	433.12	8.66	60.29
Operational stage	65,372.20	284.10	5.68	39.55
End-of-life stage	259.48	1.13	0.02	0.16
Total	165,292.06	718.35	14.37	100.00

Production of construction material and construction activities accounts for 433.12 kg CO_2-eq per square meter. Emission of CO_2-eq from the production of cement and brick only accounts for 61.12% of the total CO_2-eq emission during the material production and construction stage. Cement production accounts for the largest emission of the production stage accounting for 31.64% followed by 29.48% to produce brick. Similarly, CO_2-eq emission from coal to produce cement and brick accounts for 53.74% of the total emission during the material production and construction stage which is 53.55 t CO_2-eq. (232.7 kg CO_2-eq per square meter of building floor area).

Cement, aggregate, reinforced iron, and sand are the major components of the concrete which accounts for 59.57% of the energy and 57.32% of the CO_2eq emission of the material production and construction stage, accounting for emission of 248.24 kg CO_2-eq per square meter of building floor area. LCA conducted in France for single-family houses and multifamily houses also presented that reinforced concrete accounts for the highest contributor to the environmental impact (Hoxha et al., 2017). Wood accounts the very low emissions as the use of wood in Modern Nepalese buildings has reduced due to high prices. The detail of the emission from the material production and construction stage of the building is presented in Fig. 7. The blue bar in the figure represents the quantity of CO_2-eq emissions from the production of construction materials used in the buildings while the orange line in the graph represents the cumulative percentage of emissions from the production of the construction material used in the building.

The higher emission in the material production and construction stage of the buildings is due to the use of significant amounts of cement and bricks, as fossil fuels are used in burning brick and cement manufacturing processes. The use of alternative building construction materials like interlocking bricks and compressed stabilized earth blocks could reduce the total life cycle energy use and emission of the building (Shrestha, 2021). Local materials like wood and compressed earth have been used in traditional buildings over centuries to adapt the climatic conditions as they provide better thermal comfort and reduce operation energy (Rijal et al., 2010).

The comparative reference study of 20 studies over 17 countries (AT, BR, CN, CZ, DE, ES, HU, IT, PT, CA, NO, NP, UK, US, NZ, DE and SE) illustrates the life cycle emission from buildings ranges between 10 and 67 kg CO_2-eq per square meter per year of which production and construction stage emission range from 4 to 16 kg CO_2-eq per square meter per year (Frischknecht et al., 2020; Shrestha, 2021; Rodrigues et al., 2018) and is shown in Fig. 8. Similarly, the study on the life cycle assessment of more than 100 buildings across different countries shows that the life cycle emission of residential buildings with life span of 50 years ranges from 15 to 23.5 kg CO_2-eq per square meter per year

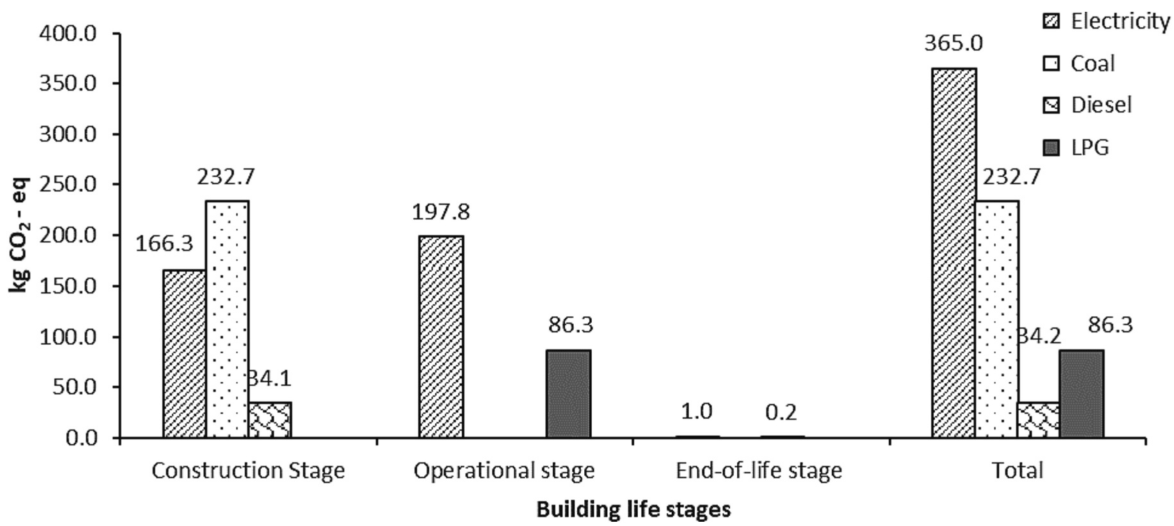

Fig. 6. Life Cycle emission from the different energy sources in all life cycle stages of the building per unit floor area.

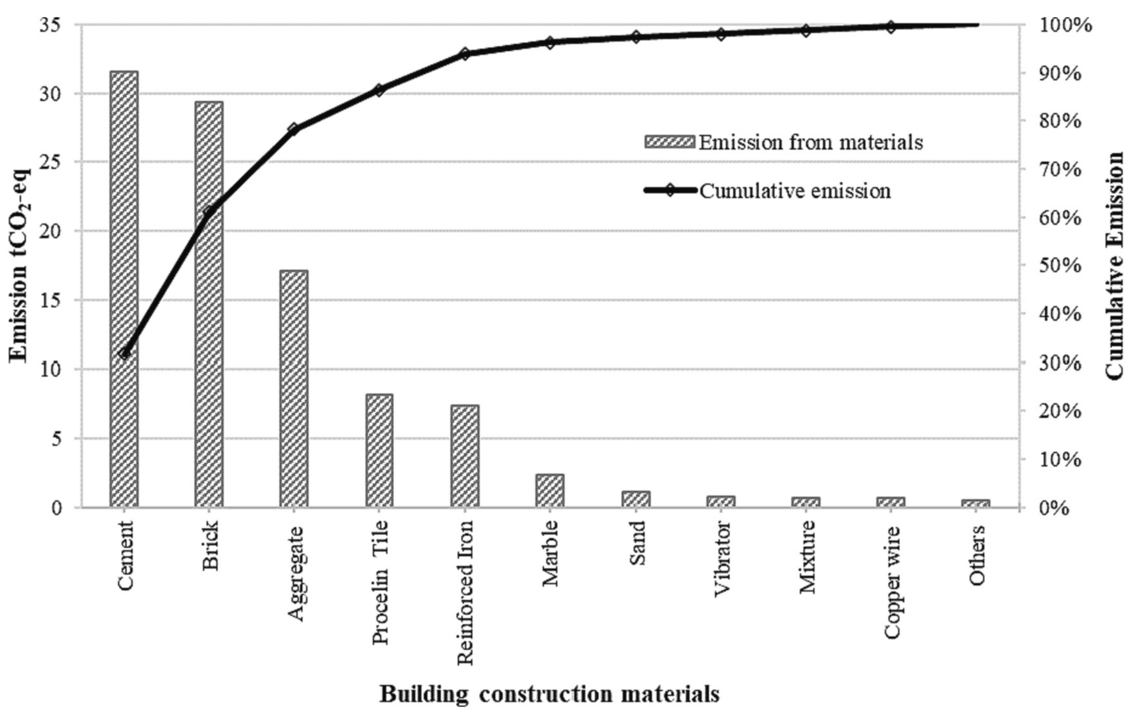

Fig. 7. Total emission from the used building materials production and construction stage of the residential building.

(Gervasio and Dimova, 2018). Compared to the studies by different authors as depicted in Fig. 8, the CO_2-eq emission in the study is low as the sub-stages B3 B4, and C3 of the building lifecycle are not considered in this study. The study by (Shrestha, 2021) in the Gorkha district of Nepal on low-rise building systems using different construction materials for the life span of 50 years shows that emission from the reconstructed earthquake-resistant houses in hilly regions ranges from 18 to 31.2 5 kg CO_2-eq per square meter per year. The CO_2-eq intensity in our study is comparable with the studies done by different authors as shown in Fig. 8. The total life cycle emission from modern Nepalese residential buildings falls in the lower range with an emission of 14.37 kg CO_2-eq per square meter per year however the material production and construction stage (Category A1 -A5) emission remains in the mid-range with emission of 8.66 kg CO_2-eq per square meter per year. This is because of lower operation emissions in Nepal due to the limited provision of the building's heating and cooling system, while the higher emission of production and construction stage is due to the use of building construction materials like concrete and burnt bricks with a higher carbon footprint.

As the production of cement and brick accounts for the largest portion of embodied energy and greenhouse gas emissions, there are no better opportunities other than moving to cleaner production of brick and cement through alternative sources of fuel like hydroelectricity and moving to greener building materials. A rapid increase in the production of hydroelectricity in Nepal is reducing the electricity import from India which will further reduce the emission of Nepal's electricity mix as the electricity imported from India has higher CO_2-eq emission due to its production from fossil fuel. With the complete replacement of the imported electricity from India with hydroelectricity generated in Nepal, CO_2-eq emission in the operational stage can be reduced by 61.85% and CO_2-eq emission in the total life cycle stage of the buildings can be reduced by 39.30%.

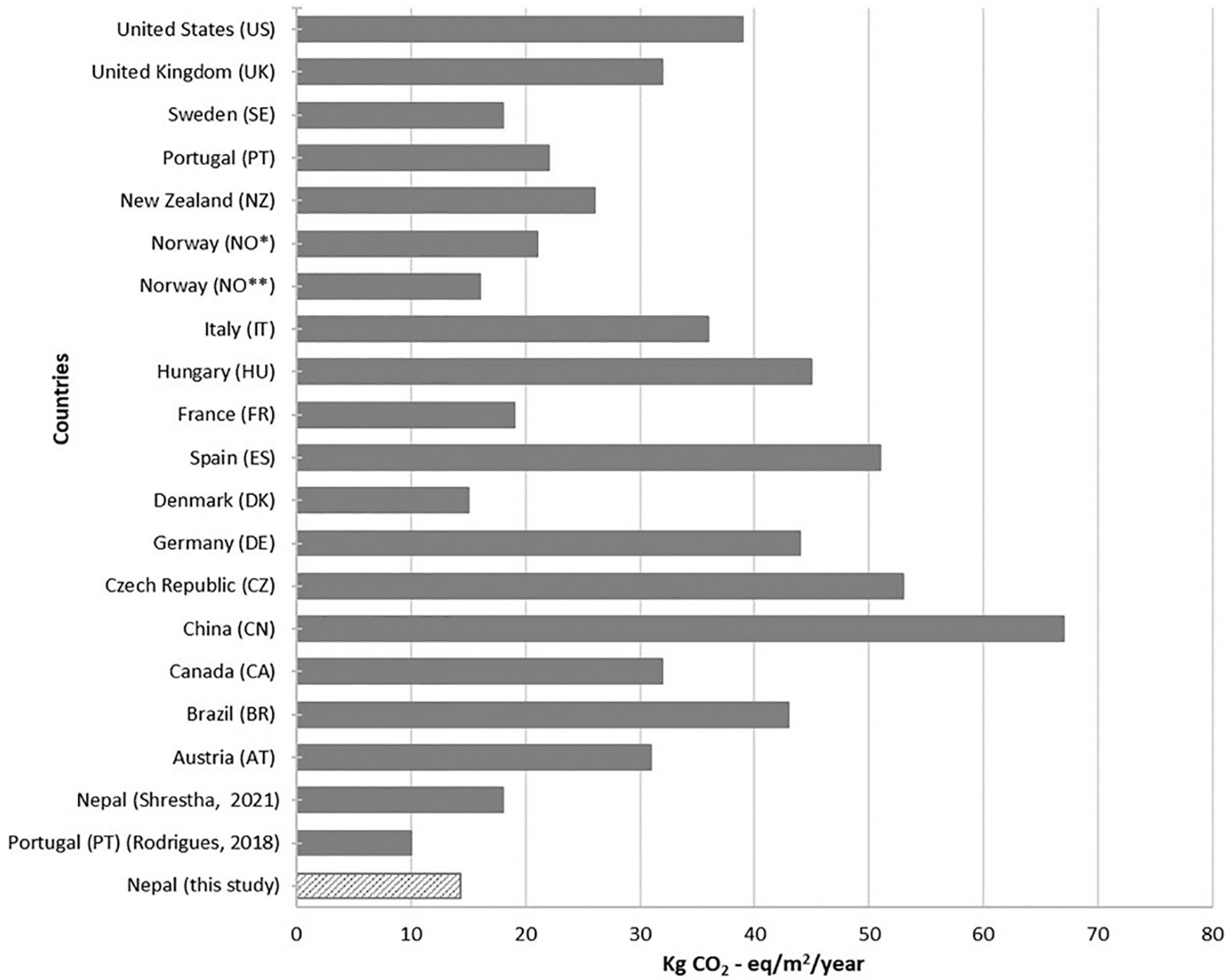

Fig. 8. *Comparison of life cycle emission intensity* (Frischknecht et al., 2020).

The major contributing factor in CO_2-eq emission from the life cycle of the two-and-a-half-story residential buildings in Nepal was the material production stage contributing 60.29% of the total CO_2-eq emission, among which Cement, brick and aggregate contributed 78.28% of the total CO_2-eq emission from material production and construction stage as presented in Fig. 7. As LCA is prone to some uncertainties due to data availability, model structures, and options available, so sensitivity analysis is done to consider these uncertainties. Among many, the local sensitivity analysis is also recommended for the LCA study (Mahmood et al., 2022). The local sensitivity analysis with 10% change in material quantity of cement, brick, and aggregate changes the CO_2-eq emission in production stage by 3.16%, 2.95% and 1.66%, respectively which is 1.91%, 1.78% and 1.00% of the total CO_2-eq emission of the building (refer to Table S1 of supplement file).

3.3. Limitations

LCA of the building used the database for the construction materials from other countries especially India or other similar regions due to the absence of local database. The unavailability of data for Nepal was the major barrier to the study. Some building construction materials are delivered with packing, and the embodied energy and the associated CO_2-eq emission of these packaging materials are not included in the study. Emission from construction and demolition waste is only considered from transportation as construction and demolition waste are usually used for refilling in construction sites and potholes of roads. The emission from the water used for construction is also only considered from transportation, as surface water is transported for construction without any treatment. The study does not cover the social and economic perspective of the buildings and is only limited to environmental factors with only focus on energy use and carbon emissions.

4. Conclusions

LCA of the building and construction materials is increasingly used in high income countries, however, there is a limited study conducted in low- and middle-income countries like Nepal. The study made a comprehensive analysis of the life cycle energy use and CO_2-eq emission of the single-family residential concrete building in Nepal with a 50-year life cycle perspective. The study results show that the production of construction material and installation accounts for almost half the total energy use and 60.29% of the total life cycle emission. Cement, brick, and aggregate account for three-fourths of the total emission from the construction phase of the building as the production of these materials uses large amounts of fossil fuel. The increasing use of concrete in modern Nepalese buildings has a significant impact on the environment and contributes to significant CO_2 emissions. The Nepalese building sector shall emphasize more on the materials that have a low carbon footprint in their lifecycle. The use of fossil fuels in material production is responsible for higher emission rates so the material production industries should move to cleaner energy. Additionally, the use of environmentally friendly materials like wood, bamboo, and stone used in traditional residential buildings should be encouraged to replace concrete and bricks while considering the structural safety of the building.

Replacement of imported fossil fuel-based electricity by the hydroelectricity generated in the country shall help to minimize the emission from buildings' energy use in Nepal. As the country plans to go carbon neutral by 2045, the promotion of induction cooking stoves over LPG shall also help in reducing the emissions significantly from the building's operational stage. With the improved lifestyle of the people, the use of building heating and cooling devices is increasing. The study on the behaviour of occupants on energy use and thermal comfort of the buildings shall further help in optimizing the energy use and minimizing the emission from the buildings. A detailed study on the life cycle of alternative building construction materials and their carbon footprint in the future shall also support in understanding of more carbon-neutral buildings.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2024.100245.

References

Biswas, W.K., 2014. Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. Int. J. Sustain. Built Environ. 3, 179–186.
cBalance Solutions, 2011. GHG Inventory report for Electricity Generation and Consumption in India. cBalance Solutions Pvt. Ltd.
CBS, 2012. National Population and Housing Census 2011. Central Bureau of Statistics, Kathmandu.
CBS, 2021. National Census 2021. Central Bureau of Statistics Nepal, Kathmandu.
Eckstein, D., Künzel, V., Schäfer, L., 2021. GLOBAL CLIMATE RISK INDEX 2021: Who Suffers Most from Extreme Weather Events? Weather-Related Loss Events in 2019 and 2000–2019. Germanwatch, Berlin. Retrieved from. https://www.germanwatch.org/sites/default/files/Global%20Climate%20Risk%20Index%202021_2.pdf.
Fenner, A.E., Kibert, C.J., Woo, J., Morque, S., Razkenari, M., Hakim, H., Lu, X., 2018. The carbon footprint of buildings: a review of methodologies and applications. Renew. Sust. Energ. Rev. 1142–1152.
Frischknecht, R., Ramseier, L., Yang, W., Birgisdottir, H., Chae, C., Lützkendorf, T., Dowdell, D., 2020. Comparison of the greenhouse gas emissions of a high-rise residential building assessed with different national LCA approaches – IEA EBC Annex 72. In: IOP Conf. Series: Earth and Environmental Science, 588. IOP Publishing, p. 022029. https://doi.org/10.1088/1755-1315/588/2/022029.
Gervasio, H., Dimova, S., 2018. Environmental Benchmarks for Buildings. European Union. https://doi.org/10.2760/073513.
GRI, UN Global Compact and WBCSD, 2015. SDG Compass. Retrieved December 05, 2022, from SDG 11: Make cities and human settlements inclusive, safe, resilient and sustainable: https://sdgcompass.org/sdgs/sdg-11/.
Herczeg, M., McKinnon, D., Milios, L., Bakas, I., Klaassens, E., Svatikova, K., Widerberg, O., 2014. Resource Efficiency in the Building Sector. ECORYS, Rotterdam.
Hoxha, E., Habert, G., Lasvaux, S., Chevalier, J., Roy, R.L., 2017. Influence of construction material uncertainties on residential building LCA reliability. J. Clean. Prod. 144, 33–47.
ICIMOD, 2009. The Changing Himalayas: Impact of Climate Change on Water Resources and Livelihoods in the Greater Himalayas. ICIMOD, Kathmandu.
IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse gas Inventories Volume 2-Energy. IPCC.
ISO 14040, 2006. ISO 14040:2006 – Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva.
Khanal, R., Upadhaya Subedi, P., Yadawa, R.K., Pandey, B., 2021. Post-Earthquake Reconstruction: Managing Debris and Construction Waste in Gorkha and Sindhupalchok Districts, Nepal. Progress in Disaster Science.
Liu, H., Li, J., Sun, Y., Wang, Y., Zhao, H., 2020. Estimation method of carbon emissions in the embodied phase of low carbon building. Adv. Civil Eng. 2020, 9.
Mahmood, A., Varabuntoonvit, V., Mungkalasiri, J., Silalertruksa, T., Gheewala, S.H., 2022. A tier-wise method for evaluating uncertainty in LifeCycle assessment. Sustainability. https://doi.org/10.3390/su142013400.
MoHA, 2018. Nepal Disaster Report 2017: The Road to Sendai. Ministry of Home Affairs, GoN, Kathmandu.
Moschetti, R., Brattebø, H., Sparrevik, M., 2019. Exploring the pathway from zero-energy to zero-emission building solutions: a case study of a Norwegian office building. Energ. Buildin. 188-189, 84–97.
MoUD, 2023. Department of Local Infrastructure, Ministry of Urban Development, 10 11. Retrieved from Work Norms: https://doli.gov.np/doligov/blog/upload/work-norms/.
NEA, 2022. Nepal Electricity Authority - a Year in Review -Fiscal Year 2021/2022. Nepal Electricity Authority, Kathmandu.
NPC, 2015. Nepal Earthquake 2015 Post Disaster Needs Assessment, vol. A. National Planning Commission, Kathmandu. Key Findings. Retrieved from. https://www.worldbank.org/content/dam/Worldbank/document/SAR/nepal/PDNA%20Volume%20A%20Final.pdf.
NSO, 2023. National Population and Housing Census 2021 (National Report). National Statistics Office, Kathmandu.
Nwodo, M.N., Anumba, C.J., 2019. A review of life cycle assessment of buildings using a systematic approach. Build. Environ. 162.
Petrovic, B., Myhren, J.A., Zhang, X., Wallhagen, M., Eriksson, O., 2019. Life cycle assessment of a wooden single-family house in Sweden. Appl. Energy 251.
Ramesh, T., Prakash, R., Shukla, K., 2010. Life cycle energy analysis of buildings: an overview. Energy and Build. 42 (10), 1592–1600.
Rasmussen, F.N., Birgisdóttir, H., 2016. Life cycle embodied and operational energy use in a typical, new Danish single-family house. In: Proceedings of the 12th Rehva World Congress, 6. Department of Civil Engineering, Aalborg University, Copenhagen.
Rijal, H.B., 2012. Thermal improvements of the traditional houses in Nepal for the sustainable building design. J. Human-Environ. Syst. 15 (1), 1–11.
Rijal, H.B., Yoshida, H., Umemiya, N., 2010. Seasonal and regional differences in neutral temperatures in Nepalese traditional vernacular houses. Build. Environ. 2743–2753.
Rodrigues, V., Martins, A.A., Nunes, M.I., Quintas, A., Mata, T.M., Caetano, N.S., 2018. LCA of constructing an industrial building: Focus on embodied carbon and energy. Energy Procedia 153, 420–425. https://doi.org/10.1016/j.egypro.2018.10.018.
Shrestha, J.K., 2021. Assessment of energy demand and greenhouse gas emissions in low rise assessment of energy demand and greenhouse gas emissions in low rise earthquake in Nepal. J. Build. Eng. 34, 101831.
Thapa, P., Mainali, B., Dhakal, S., 2023. Focus on climate action: what level of synergy and trade-off is there between SDG 13; climate action and other SDGs in Nepal? Energies. https://doi.org/10.3390/en16010566.
UNEP, 2022. United Nation Sustainable Development Goals. (United Nation Environment Program). Retrieved December 5, 2022, from sustainable cities and communities: https://wedocs.unep.org/bitstream/handle/20.500.11822/22746/11_Sustainable%20cities%20and%20communities_FINAL.pdf?sequence=1&isAllowed=y.
UNFCCC, 2017. United Nation Climate Change. Retrieved 12 07, 2022, from. https://unfccc.int/news/rapid-urbanization-increases-climate-risk-for-billions-of-people?gclid=Cj0KCQiAkMGcBhCSARIsAIW6d0AhcHxzMOM4YQ5Pd4vSkWhVYwVcGgGRN8sWAioYmfzcwnCHz5Zly70aAiWxEALw_wcB.
Varun, Bhat I., Prakash, R., 2012. Life cycle analysis of Run-Of River small hydro power plants in India. The open renewable. Energy J. 11-16.
WBG and ADB, 2021. Climate Risk Country Profile: Nepal. The World Bank Group and Asian Development Bank, Kathmandu.
World Bank, 2022. Country Climate and Development Report Nepal. The World Bank Group, Washington.