Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2025, Volume 13, Issue 2, 1130580

Original Research Article

Towards Sustainable Conventional Indian Houses: Linking Embodied Water-Energy Nexus to Pro-locals' Architecture, Construction and Regulatory Reforms with Lifecycle Assessment and Scenarios Methods

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Cite as: Sharma, A. K., Chani, P. S., Jha, A. A., Towards Sustainable Conventional Indian Houses: Linking Embodied Water-Energy Nexus to Pro-locals' Architecture, Construction and Regulatory Reforms with Lifecycle Assessment and Scenarios Methods, J.sustain. dev. energy water environ. syst., 13(2), 1130580, 2025, DOI: https://doi.org/10.13044/j.sdewes.d13.0580

ABSTRACT

Real-world insights to conserve water in constructions without overshooting embodied energy meet sustainable development goal 12, specifically in the current thirsty world. The study aims to outline conclusive strategies to conserve embodied water and embodied energy, together with regulatory insights. Following the ISO 14046 and ISO 14044 frameworks, the experiment accounts for cradle-to-gate lifecycle assessment, taking Jammu's conventional houses in India as cases. Observing top-impacting embodied water materials differ from embodied energy ones, the experiment delves into the appraisal of 'threats' and 'opportunities' in locals' preferences using the scenario manager technique. Not only was the embodied water and embodied energy offsetting achieved by almost 30%, but the flexible scenarios suiting economically diverse users also have significant pragmatic worth. While the recommendations base is the embodied water-energy nexus and retains societal interests, indeed, the methodology and study's implications are global and replicable. The experiment meets the three pillars of sustainability and thereby remarkably boosts the sustainable building practice.

KEYWORDS

Embodied water, Sustainable buildings, Energy-water nexus, Sustainable construction, Design-decision making, Scenario manager analysis, Lifecycle assessment.

INTRODUCTION

Multiple sustainable development goals (SDGs) align with energy and water efficiency. Specifically, SDG 12 talks about responsible consumption and production, which relates to doing better and more with less. However, energy conservation measures have extensively revamped production processes and the construction sector. Energy consumption in the production of building materials and lifecycle energy use in buildings have been intervened sufficiently [1]. Building professionals choose materials based on low embodied energy (*EE*), which demands minimum operational energy during the occupation phase of building life [2].

However, the freshwater crisis is a priority on the agenda. Indeed, life is impossible without water. Responsible water use is vital to meet sustainability before it is too late. SDGs also

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greatly emphasise the availability and access to water. Endangered future water availability stimulates climate-resource nexus studies [3]. Thus, water-energy nexus exploration is the new normal in scientific research [4]. Integration of energy-water-centred planning is required to promote sustainability [5]. There are sufficient energy-water-carbon [6] and energy-water-food [7] nexus studies at the urban level. Alternate and renewable energy sources of water and energy production are in contention [8]. Although product water footprints have also emerged in the last 10–15 years [9], only the operational water required during the building occupancy phase is somewhat intervened in countries like Australia [10]. Meanwhile, given that the constructions consume 1/5 of the globally accessible freshwater [11], which is of predominantly potable standard, embodied water (*EW*) research is strikingly negligible. Moreover, linking design and construction methods to embodied impacts excludes *EW* [12, 13]. Two significant reasons were observed: *EE* obsession in previous decades and the negligible monetary value of water vis-à-vis energy.

India has access to only 4% of global freshwater but accounts for 1/4 of global water extraction annually to feed almost 1/5 of the world's population it holds [14]. Indian constructions are not only water intensive in general [15], but the energy consumption of the Indian building construction sector is immense [16] and determinantal in defining global energy consumption. However, due to the population and the employment ecosystem in the Indian cities, the plethora of new houses in the peripheries of small towns presents a hefty challenge to contain. As a result, conventional houses are the dominant construction type in the Indian building construction sector. The water supply and borewells are conventional constructions' dominant water sources. The borewells contribute to the non-revenue water while water-supply charges are negligible or managed to absolute nil. Water purchased through tankers for construction was rare but is increasing now in many locations with the dip in groundwater and some strictness on digging the domestic borewells. However, the intervention in conventional houses is bleak, especially from the *EW* point of view, as care and unaccountability towards water use in such constructions have never been considered. Given the ongoing infrastructure development and requirements in India, intervention in its conventional houses can regulate the country's energy and water consumption [1, 17–20].

The water used by the buildings during their lifecycle is termed the lifecycle *EW* of buildings, which is similar to the *EE* terminology. However, in general terms, all water used in material production and extraction is termed 'embodied water' or 'materials embodied water' [21]. It is also sometimes called the cradle-to-gate lifecycle phase 'embodied water'.

The life cycle assessment (LCA) approach advocated by ISO 14040 frameworks, including 14044 for energy and 14046 for water footprints, calls to outline the inputs and corresponding environmental impacts for the product's entire life cycle, known as cradle-to-grave assessment. In this study, a building construction project is selected as a product. The fact that the use (operational) phase of the building has largely been looked into by researchers for energy and water use optimisations, the construction phase, and specifically the phases prior to that remained missing, particularly for *EW* assessments. Even though few authors [20, 22] could assess two or more phases together, i.e. cradle-to-gate, gate-to-site, and construction phases together, there are very scant studies on *EW* and talks about one LCA phase, for example, cradle-to-gate [21] or construction [23] phase mostly. Hence, due to data unavailability issues involving water consumption in the construction projects, attempting cradle-to-grave LCA studies remains missing, and likewise, the current study looks to outline the consumptions in the larger perspective of the aim envisaged for cradle-to-gate phase only. Nevertheless, *EW* studies are a nascent and scant research area, and they stimulate a knowledgeable audience to foster new interventions. The fact that the energy-water nexus is looked into, the study is definitely a worthwhile addition to the weak research bank. At the same time, the lack of data availability for energy-consumption data further insists on carrying the study for one LCA phase (cradle-to-gate) for the time being.

Figure 1 illustrates various lifecycle phases for a construction project from the view of *EW* and *EE* assessments. It also outlines the phases involved in a generic LCA approach for a product. **Figure 1** categorically details the life cycle phases involved in a building construction project through visuals and markers. The phase-wise impacting parameters for *EW* and *EE* are outlined. At the same time, various types of direct and indirect consumptions involved in the construction project are also defined for each of its lifecycle phases. As illustrated in **Figure 1**, cradle-to-grave assessment consists of a combination of cradle-to-gate, gate-to-site, construction phase, use (operational phase) and demolition phases. Lifecycle assessment studies, both for *EW* and, in general, for any product, usually also take into consideration the direct and indirect resource consumption attributed to humans involved in the entire process. Accordingly, humans emerge as a vital component in all the lifecycle phases in the current study, as **Figure 1** illustrates. Indeed, cradle-to-gate and gate-to-site are invariably grouped as a cradle-to-site phase, also known as pre-construction phase. As justified for the data availability reasons and especially to outline the water-energy nexus for a construction project, the current study considers only the cradle-to-gate phase, as highlighted in the bottom half of **Figure 1**.

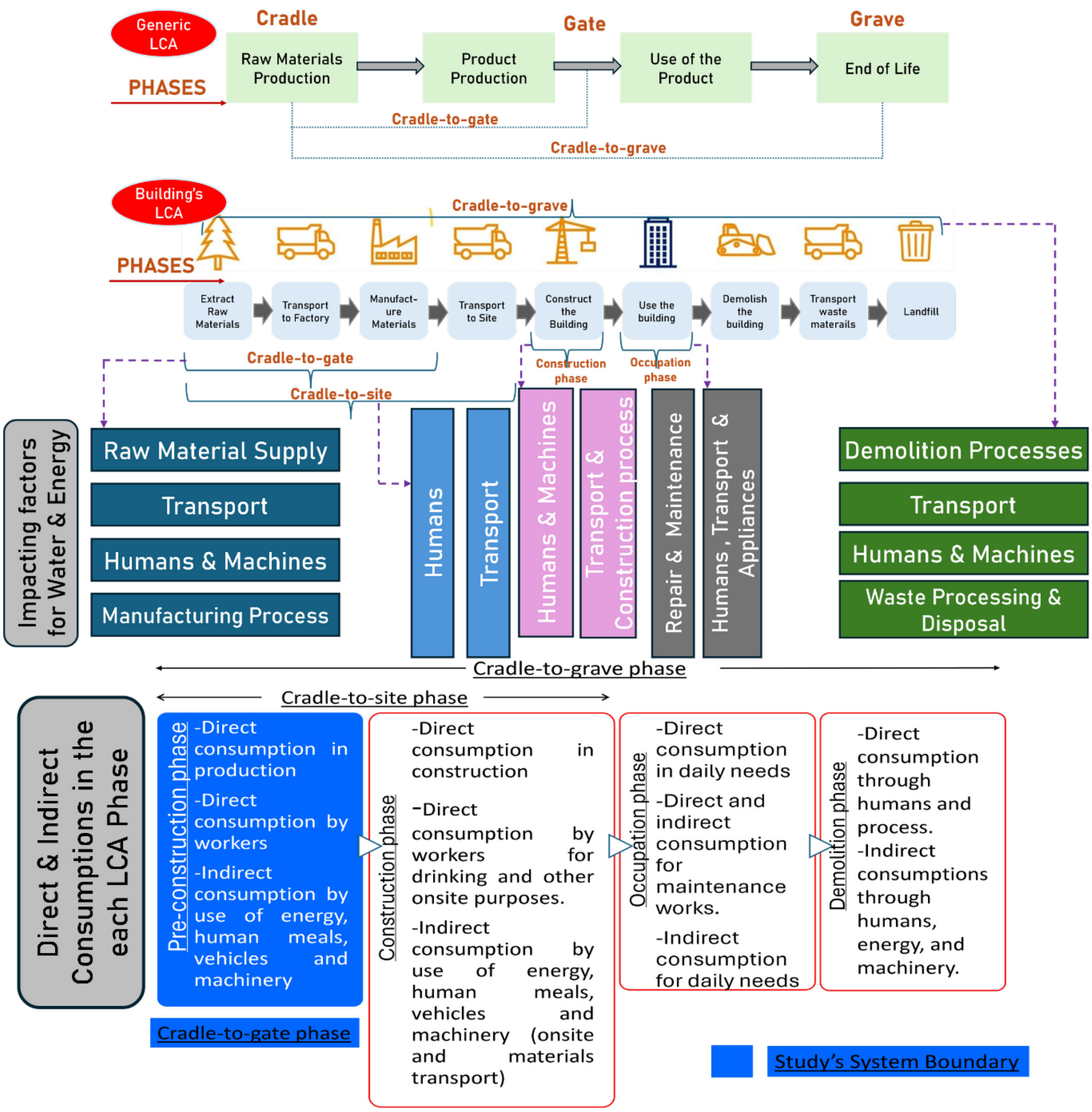

Figure 1. Buildings' lifecycle phases and detail of the study's system boundary

The literature signifies that the terms 'virtual water' [24], 'indirect water' [25], and 'water footprint' [23] refer to *EW* determined for differential system boundaries of building construction. The water footprint also includes grey water footprint (polluted water) [26]. However, the construction water footprint is limited to the blue water footprint (freshwater consumption). A 2022 study [20] exclusively defined the term 'embodied water' for building construction projects and boundary conditions. The study also put forth consistent terminology for the unit material-wise consumption quantities termed as 'embodied water coefficients (EWC)' to remove the intricacies of different terminologies used in the past water footprint intensities (WFI) or water consumption intensities (WCI). As it turns out, subsequent studies from Australia [27], India [21, 28], and the USA [11, 29] manifested the same terminology use, and thus, the *EW* domain is streamlining for the better. Carrying forward the consistent terminology use and in consonance with the consolidated *EE* domain, the current study uses the terms *EW* and *EE* for the water and energy consumed in the cradle-to-gate lifecycle phase of building construction.

As also shown in **Figure 1**, *EW* – similar to *EE* – has two components. One is the physical water used in production and manufacturing, known as 'direct *EW*'. Other factors are the 'indirect *EW*' consumed for the energy used in materials production, water used by the workforce employed, and water attributed to the fuel and machinery used and all the complex processes used in production. While literature signifies the importance of carrying *EW* or *EE* studies even with a single building, the current study incorporates three conventional houses. Contributing to the scarce *EW* domain is realistically nascent; however, the advanced vision to look at the embodied energy-water nexus with the larger aim of optimising it makes the study a worthwhile stimulus for advanced sustainable built environment research.

The various main sections of the paper are: Introduction, study's aim, previous research, and study area; Materials and methods; Results and discussion; Conclusion, followed by Acknowledgement, References, and Appendix.

Aim of the study

The evolution of the study rests on the literature gaps of the domain exclusively explained in the following sections. The exploration is based on the hypothesis that 'It is possible to achieve offsetting of *EW* & *EE* simultaneously in conventional houses through design decisions and policy insights that value the local strengths and construction practices.' Such an approach is inevitable to have promising real-world applicability and a pragmatic nature.

The study aims to identify evidence-based & flexible-design decision-making, along with users & policy insights to offset *EW* & *EE* of conventional Indian houses. The study banks on the following objectives:

- To outline the best predictors (in materials and construction practices) comparatively in *EE-EW* nexus aspects from the site data.
- To align the best predictors and the locals' interests to arrive at enough flexible solutions by involving local stakeholders.
- To tabulate design considerations and preliminary policy interventions vis-à-vis observations made and inputs of local experts, which also cater to sizeable societal diversity in income levels.

The study is a significant boost to the scientific knowledge bank in the following manner:

- Not only is the scant *EW* research contributed, but the outcomes' base is also *EE*. The *EW-EE* nexus is focused on seeking better sustainable building solutions.
- The experiment has an underlying pragmatic prerogative of local-centric insights, and its implications have enhanced real-world applicability and embraceability. Locals – both the houses' owners and workers, local construction practices, their varied economic levels and corresponding material preferences are intervened.
- The study also stands out in not seeking alternate & non-native solutions vis-à-vis their fitment in onsite realities. Only the prevailing construction techniques are evaluated and

tweaked towards goal-seeking, with the understanding that prevailing practices are locals-centric and are there to stay for a more extended period.

- Based on the *EE-EW* nexus, architecture plus design (A+D) decision-making through scenario manager application with local experts' involvement makes the experiment notably novel. Never before were such realistic leads for varying kinds of the societal lot sought.
- The evolution is comprehensive in augmenting sustainable building practices. It meets all sustainability dimensions – environmental (*EE-EW* nexus), socio-cultural (locals' preferences & native practices) and economical (varying economic levels of locals).
- Because the experiment is simplified and field-specific with commendable real-world application, it is inevitable to replicate it across regions of varying contexts to advance sustainable building practices further.

Previous research

While the vitality of water resource availability due to the massive constructions was first examined by Australian researchers in 2004 [30], the growth in *EW* research remains below par. Australian, USA and Indian researchers have made few scholarly *EW* contributions in the last 20 years. However, the emphasis is still on sparking the researchers elsewhere. The first Indian *EW* study emerged in 2011 [31], and follow-up studies [32, 33] till 2022 show significant similarity in the methodology and system boundary limitations to the 2011 one. The rejuvenated approach for *EW* assessment in developing nations, explicitly considering the low monetary value associated with water, is argued in an in-depth Indian study [17]. A 2022 study [20] proposed a significantly improvised *EW* assessment framework, replicable for most developing countries and encouraged *EW* studies across contexts and regions. A USA research group has also developed a few *EW* studies [34, 35] in recent times using the stable and developed economy of the USA through a methodology better known as input-output analysis.

Auditing all the production process steps is almost impossible, which returns underestimation in the process-based lifecycle assessment method. Contrary to the bottom-up assessment involved in process-based methodology, the top-down assessment approach often overestimates consumption and is known as Input-output (I-O) methodology. Including some unnecessary sectors in the calculations explains the overestimation of the I-O method. For the Indian industry, economy-based I-O data are invariably unavailable. At the same time, the economy's instability is another question in the present world order vis-à-vis stable economies like the USA and Australia. Furthermore, the economic equivalency of water and energy consumption is incomparable in the field scenarios. So, an accurate picture of water consumption is difficult to achieve with the I-O method in the Indian context. Given the present *EW* data bank and the awareness, using hybrid methods or triangulation approaches is not a bar to carry the *EW* studies [28]. However, process-based methods following the bottom-up assessment are a fitting way to go in developing countries. The bottom-up approaches of *EW* [36] and *EE* [37] assessment were also observed for Indian constructions.

Most *EW* studies before 2022 focused on quantitative assessments as *EW* contemplations bear a toddler and exploring research status. However, few could foresee the *EW* linkage to energy at the building level and attempted *EW-EE* nexus studies. Proponents have recently outlined the carbon-energy-water nexus for building construction [11, 21]. **Table 1** details the various construction *EW* studies that involved its nexus to *EE* and embodied carbon (*EC*).

Table 1 clearly illustrates that the USA's researchers are more inclined to *EW-EE* nexus research but consistently use the I-O data of the USA's developed economy. Indian studies, such as [21, 28], showcase the more reliable approach, which is suited to developing economies and process-based assessments following material inventories. Both USA and Indian results show uniformly in the *EW-EE* correlation, but in-depth findings at the material level were more detailed in Indian studies.

Table 1. Literature of embodied water-energy nexus studies (*EW* – Embodied water, *EE* – Embodied energy, E*C*-Embodied carbon emissions, na – not available)

Study	Building types covered	Country	Components covered *EW*	*EE*	*EC*	Significance and outcomes
[28]	Three conventional houses	India	✓	✓	na	Results are the average impact of the two databases. Outcomes promote the use of global databases in any context. *EW* and *EE* share a weak and inverse correlation.
[21]	Four low-rise masonry houses	India	✓	✓	✓	Used EPiC database for assessment. *EE* and *EC* are directly and positively related, *EW* offsetting requires a different approach.
[34]	Five institutional buildings	USA	✓	✓	na	Energy-related *EW* was also assessed. *EW* and *EE* are weakly correlated.
[11]	Four university buildings	USA	✓	✓	✓	USA I-O benchmarking data-based study. A decrease in *EE* may not offset *EW* much. *EW* offsetting needs special efforts.
[29]	One generic reinforced concrete building	USA	✓	✓	✓	The study analysed the 5 different configurations in concrete and steel of a generic building. Computations used a hybrid model based on USA's I-O data. Results show that horizontal building configurations uniformly benefit *EE*, *EW*, and *EC* more than vertical ones.
[38]	One university building	USA	✓	✓	✓	Study basis is I-O data of USA economy. Total *EC* and *EW* are positively and strongly correlated at the building level but weakly correlated at the material intensity level. *EW* should also be a criterion behind selecting building materials alongside *EE* or *EC*.
[39]	Building materials only	USA	✓	✓	na	The study aimed to examine trade-offs between *EW* and *EE* in selecting building materials. Outcomes indicate a weak correlation between *EW* and *EE* for materials. Material selection in construction is, therefore, decisive.
[40]	Ten higher education buildings	USA	✓	✓	na	Total *EE* and electricity *EE* share a direct and positive relationship with total *EW*. This relationship considerably weakens at the material level. *EW* reduction needs significant efforts beyond reducing *EE*.
[41]	One higher education building	USA	✓	✓	na	The study aimed to assess trade-offs between energy and water. It adopts multi-objective-generic algorithm with envelope materials & window to wall ratio (WWR) as optimisation variables for simulation. *EW* and *EE* show reverse behaviour to WWR. Overall results show *EE* optimisation can drastically increase *EW* & vice-versa.
[42]	One commercial building	Australia	✓	✓	na	Hybrid analysis was used based on Australian I-O data. Australian buildings are significantly *EW* and *EE* enriched. The assessments' accuracy relies on data quality & availability.

The positive and direct relationship between embodied energy and embodied carbon is evident in the building construction sector [21]. It explains the massive *EE* research [43] followed by net zero mission [44] and carbon-led sustainable programs of different nations [45]. A Chinese study advances to explore the energy-cement-carbon nexus vis-à-vis the prospective urbanisation in China [46]. The sustainable use of building materials in architecture and construction is very much in focus [47].

Table 1 also includes the solitary attempt of Australia [42], which involved the I-O data of the Australian economy. However, the correlation between *EW*-*EE* remains consistent with those of other global efforts. Through Table 1 studies, not only is the importance of *EW* outlined, but it has also been found that conserving *EE* measures over the decades is insufficient to have *EW*-conscious buildings [39]. Thus, *EW*-conservative buildings definitely demand fresh and innovative insights from building researchers, as Table 1 studies uniformly seek.

The water-specific focus remains out of consideration in most building-specific research and field contributions [13]. While the trade-offs between *EE* and *EW* have been predicted [48], the direct or indirect linkages between *EW* and *EE* need consolidation. Another limitation of the literature calls to advance the *EW* quantifications to the corresponding measures in the Architecture plus design (A+D) phase and policy-level decision-making. Indian *EW* studies of 2022 [20] and 2024 [28] relate quantifications to some extent to A+D measures. However, a concrete approach or evidence remains elusive. A recent study from the USA sees the linkage of building surface aspect ratio to resource consumption [29]. An Iranian research group established the *EW* assessment for building typologies based on various building elements [49]. Through a follow-up study, they outlined the sustainability of Iranian vernacular architecture based on water consumption parameters [50]. The fact that researchers see the worth even in assessing drinking water consumption by construction workers during the onsite construction phase [51] is worthy enough ground to contribute more and more *EW* studies. While proponents argued [40, 41] that *EW* conserving design measures would increase *EE* and vice-versa, seeking *EW* & *EE* conscious design decisions is novel. No study has focused on the real-world applicability of *EW*-*EE* nexus-based design decisions, taking various local strengths and varying users' economic levels as one size does not fit all. So, furthering design insights to user-level and policy-level actionable takeaways return invaluable takeaways towards 2030 SDGs and strengthen sustainability practices.

Study area

The study explores conventional houses in Jammu. The city is on course towards becoming another urban centre of modern India, specifically after the change of Jammu and Kashmir's special legal status in 2019. Moreover, its location suits education, business, and safety vis-à-vis other parts of Jammu and Kashmir, a union territory in India.

Table 2. Detail of the cases

Description	CJH-1	CJH-2	CJH-3
Plot area [m^2]	125	250	116
Total construction area [m^2]	107	380	105
Number of floors	1	2	1
Building type	Stand-alone family house in plotted development		
Location	Jammu		
Project completion year	2021	2022	2021
Type of structure	Composite (few RCC columns with load-bearing ceramic brick walls)		
Concrete mixing	In-situ		

The rising peripheral houses, built by the migrated population to Jammu, are primarily low-rise conventional houses. Rarely are the documented mixes and specifications followed in their constructions. Indeed, masons, in consultation with house owners, volunteer for the design and construction decisions of the houses. The conventional houses of Jammu have already proved high in *EW* [20] and *EE* [52] consumption. The consumption indexes are worse if the share of non-revenue water and energy and the water and energy supply leakages are also considered because data reveal a 30% leakage attributed to Jammu City's water supply [19].

Table 2 outlines the pertinent details of the three houses, herein referred to as CJH-1, CJH-2, and CJH-3. These houses represent conventional construction in terms of construction technique, materials, location (type of construction personnel involved) and years of construction (uncontrollable factors like weather).

MATERIALS AND METHODS

The following sub-sections detail the research design in terms of methods, tools, system boundary, scope & limitations. The inventory and impacts are elaborated before leading into subsequent stages, as per the ISO frameworks followed.

Methods

In principle, both ISO 14046 LCA [53] and water footprint network methodology are similar for water footprint assessment. The only difference lies in the dissimilar objectives of quantitative assessments and results interpretation. The current approach extends the same water footprint approach to the *EW* assessment and includes interpreting results. A similar chronology of assessment also exists for environmental management-based ISO 14044 LCA methodology [54]. Hence, following the joint preview of the *EW*- and *EE*-based assessment methods and generalised steps for LCA, the detailed study methodology is framed and illustrated in **Figure 2**. As the literature also shows, the current study only follows the verticals defined by the ISO frameworks, keeping in view both *EE* and *EW* assessments together, along with the scope and limitations. The impact categories are framed as common ones for *EE* and *EW* and range from outlining the consumptions at the unit level and aggregate level to further focusing on per unit construction area of the houses taken, as subsequent sections explain.

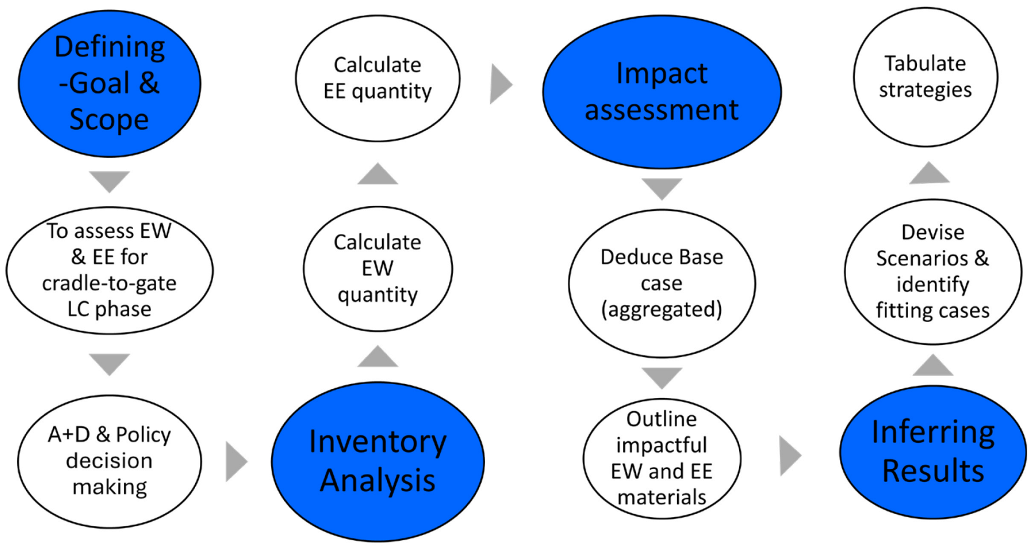

Figure 2. Detailed methodology illustration

The highlighted shapes in **Figure 2** indicate essential LCA verticals, i.e., goal and scope definition, inventory analysis, impact assessment, and results interpretation. Other shapes outline the primary operations under each vertical in chronological order, as followed in the study. After the goal and scope definition, *EW* and *EE* quantifications are carried out. Afterwards, the impacts are assessed in light of impacting materials, which leads to further inferential analysis through scenario-making exercises. Finally, various scenarios are framed and compared with the base case to deduce the pertinent insights.

Defining the boundary conditions

The boundary conditions are chosen to understand the *EW* and *EE* impacts in the pre-construction phase, which comprises materials selection, A+D, and other preferential decisions influenced by economic affordability and policy impositions. So, the cradle-to-gate lifecycle phase of construction is covered. In contrast, the construction works, occupation, and demolition phases are kept out of scope, as shown in **Figure 1**, depicting conventional house construction's various life cycle phases vis-à-vis *EW* and *EE* consumptions, also showing the study boundary and the different parameters involved for each of the life cycle phases. As the literature encourages, the various processes involved in the cradle-to-gate phase are holistically covered by consulting EWCs and EECs – but specifically from the Indian ones. The building furniture, furnishings, PVC conduits, and sanitary fixtures are excluded from the material inventory, while the inventory is up to the ready-to-move-in phase of the houses, including external plot development. The boundary is limited to 10 top impacting materials, as previous studies and local experience urge.

Tools and techniques

The research study uses the following tools and techniques:

- A generalised assessment chronological approach as provided by the ISO 14044 and ISO 14046 LCA frameworks.
- The scenario manager technique tweaks the prevalent material combinations and construction techniques to offset *EW* and *EE* simultaneously.
- Quota sampling technique, as the availability of material inventory to precision, is a vital dimension behind the final selection of the cases and is ensured through field investigations and consistent site visits.
- A cross-sectional technique allows the selection of the houses that are completed in all respects before data collection. It ensures that the selected houses bear a resemblance to uncontrollable factors like climate and simultaneously are not located at distant locations from each other. Besides being constructed in almost similar calendar years, they are also the typical representatives of the local conventional constructions.
- The approach is centred on sustainable development tools through locals' participation to seek local-centric design decision-making & other regulatory interventions.
- Data charts and tornado plots are used for analysis and data interpretation.
- The assessments refer to the latest Indian databases for material-wise hybrid embodied coefficients.

Scope and limitations

The exploration is limited to the cradle-to-gate phase, only considering material quantities for *EW* and *EE* assessment. Energy and water use attributed to the complex bottom-up production steps is interpreted using embodied energy and water coefficients from the latest Indian literature. The analysis builds on three houses against the literature evidence of involving even one case in many studies. The extent of availability or devising accurate material consumption data (inventory) is the dominant criterion behind the selection of houses, besides these to be the ideal representative of conventional constructions of the region. The scope relies on accurate data availability, so only 10 materials are assessed, which are indeed the top-impacting *EW* or *EE* materials outlined in previous research. Moreover, the author's familiarity with the local constructions helps to choose the selected materials and pertinent houses.

The study limits to the local expert's assumptions-based material quantities in the scenarios because of invariably lesser use of documented mixes, specifications or technical inputs during the conventional constructions. Prospective studies using software for specification, design and policy-based iterations may yield slightly varying results. However, involving and valuing locals in decision-making nudges the sustainability approach. Scenarios involving alternate building materials are kept out of scope, as are the scenarios that intervene in the onsite construction phase. For devising the scenarios, the average of the three cases is taken as a base case rather than any case from the literature. With an understanding that there can be other scenarios, the experiment is limited to 10 pertinent scenarios with the available experts, time, and other resources for this study. Moreover, a lasting attempt is made to consider varying societal sections economically to assess and improvise the ongoing building regulations, policy reforms, people preferences and A+D practices. Given that the cost implications of the solutions still need to be verified, the study's potential scenarios are devoid of its economic viability check, which can be considered a limitation.

Inventory

The exercise relies on precise inventory availability with the site owners/contractors, which is seldom the case for conventional houses in Jammu. The survey exercise had to access 90-plus houses, predominantly those already completed, to arrive at the pertinent cases. Data quality and consistency were highly prioritised throughout the entire exercise. Only such cases were selected where the inventory was comprehensive and easy to relate to the physical construction for verification, and in addition, the contractors, masons, and house owners were approachable for queries on inventory formulations. Authors have also attempted an exercise to access the same houses and contractors involved by different sets of observers during the gap of six months from the initial selection of the houses. The uniform & satisfactory set of information collected in both instances only led to the final analysis as per the research design. Further, one building's availability for many embodied energy- or water-related studies was an encouraging factor in selecting the three houses.

Another dimension behind the houses selected was the contribution of uncontrollable parameters related to the weather of the place. All the houses are located sufficiently close in the same region and constructed almost in the same calendar years, so the weather impacts on energy and water consumption are uniform in all cases. All the houses were ideal representatives of conventional construction. The materials, techniques and personnel involved are typical of the region vis-à-vis conventional house constructions.

Table 3 depicts the inventory for all the ten materials covered in the study for each disaggregated case, as collected by field investigations and onsite records available. The study follows the functional units for the material quantities as per the utilised database. The database values depict water consumption [kL] per unit material quantity [FU] consumed, herein specified as [kL/FU] and labelled as hybrid embodied water coefficients (EWC). As per literature, hybrid accounts for the contribution of all complex 'direct' and 'indirect' components involved in the production process (including upstream processes and humans involved), as **Figure 1** shows and are computed by both the bottom-up and top-down LCA approaches (as applicable) to arrive at the final value.

Notably, the material inventory is available in conventional site units, which at times differ from the functional units (FUs) of the database values consulted for unit material consumptions. So, such values stand converted through standard conversion factors of Indian materials to arrive at the corresponding values in units in consonance with the FUs of hybrid EWC consulted from the databases, as shown in **Table 3**. For example, the cement inventory is available in bags number (50 kg each). Accordingly, units are transformed into desired 'metric tons' to suit the database units. However, steel (in 'metric tons') and brick (in 'numbers') units did not invite any conversion.

The EWC (α) values are sourced from notable recent Indian studies [20, 21, 28]. Besides the material-wise consumption for each house and the respective EWC, Table 3 also includes the total material consumption in aggregate case CJH-A, in the FUs at par with the FU of the database consulted.

Table 3. Material inventory for embodied water assessment; EWC values according to [20, 21, 28]

Material	Functional Unit FU	House-wise material inventory Q [FU]				EWC 'α' [kL/FU]
		CJH-1	CJH-2	CJH-3	CJH-A	
Brick	1	22,000	42,000	20,000	84,000	0.0053
Steel bars	t	2.5	8	2.3	12.8	98.6400
Cement		22	55	19	96.0	8.5200
Sand	m^3	119	410	82	611.0	3.5700
Coarse & fine stone aggregates (S_A)		111	335	108	553.5	3.5000
Ceramic/Vitrified tiles (C_T)	m^2	111	249	78	437.6	1.1200
Float glass		23	11	30	64.0	4.1480
Security glass		0	88	0	88.3	15.4800
Paint		1593	3348	1582	6523.0	0.2100
Plywood		24	345	17	385.8	4.0300

Like Table 3, Table 4 illustrates the material-wise consumptions for the aggregate and disaggregated cases in similar units to the hybrid embodied energy coefficients (EEC) notated by 'β'. The site data invariably return a uniform conventional unit employed locally. Still, to suit the scientific databases, these units are converted into database units using standard conversion factors for the Indian context. For example, the standard Indian ceramic burnt brick of size 230 mm × 115 mm × 75 mm, having a standard mass of 3.5 kg, is used in Jammu. Table 4 supports calculating the *EE* for a house or all the houses taken together (CJH-A). The process also efficiently evaluates material-wise *EE* consumption for each house and the aggregated case.

Table 4. Material inventory to assess embodied energy

Material	Functional Unit FU	House-wise material inventory Q [FU]				EEC 'β' [MJ/FU]
		CJH-1	CJH-2	CJH-3	CJH-A	
Brick	kg	77,000	147,000	70,000	294,000	3 [55]
Steel bars		2500	8000	2300	12,800	30 [56]
Cement		22,000	55,000	19,000	96,000	6.4 [56]
Sand		203,490	701,100	140,220	1,044,810	0.11 [56]
Coarse & fine stone agg. (S_A)		167,760	503,978	163,816	835,554	0.05 [57]
Ceramic tiles (C_T)		4440	9944	3120	17,504	8.2 [56]
Float Glass		229	110	299	638	15 [55]
Security Glass		0	1762	0	1762	30 [27]
Paint		142	298	141	581	80 [55]
Plywood		221	3205	158	3584	16.5 [55], [56]

Impact assessment

The following equations deduce the quantitative impacts of *EW* and *EE* for each house.

$$EW = \sum_{j=1}^{10} \left(\alpha_j Q_j\right) \quad (1)$$

$$EE = \sum_{j=1}^{10} \left(\beta_j Q_j\right) \quad (2)$$

Where Q_j [FU] is the quantity of *j*-th material (among 10 materials) represented in functional units.

Accordingly, Table 5 details the *EW* of each disaggregated house and the aggregated case (CJH-A) in a couple of ways – material-wise *EW* consumption and total consumption *EW* considering all the materials together. Similarly, Table 6 showcases the material-wise *EE* consumption and total *EE* consumption for the disaggregated and aggregated cases.

Table 5. Material and house-wise embodied water assessment detail

Material	House-wise and aggregated *EW* [kL]			
	CJH-1	CJH-2	CJH-3	CJH-A
Brick	116.2	221.8	105.6	443.5
Steel bars	246.6	789.1	225.9	1261.6
Cement	187.4	468.6	161.9	817.9
Sand	424.8	1463.7	292.7	2181.3
Coarse & fine stone aggregates (S_A)	387.1	1172.2	378.0	1937.3
Ceramic/Vitrified tiles (C_T)	124.3	278.4	87.4	490.1
Float glass	95.4	45.6	124.4	265.5
Security glass	0.0	1366.9	0.0	1366.9
Paint	334.5	703.1	332.2	1369.8
Plywood	95.9	1390.4	68.5	1554.8
Total *EW* [kL]	2012.3	7899.7	1776.6	11,688.6

Table 6. Material and house-wise embodied energy assessment detail

Materials	House-wise and aggregated *EE* [MJ]			
	CJH-1	CJH-2	CJH-3	CJH-A
Brick	231,000	441,000	210,000	882,000
Steel bars	75,000	240,000	69,000	384,000
Cement	140,800	352,000	121,600	614,400
Sand	22,384	77,121	15,424	114,929
Coarse & fine stone aggregates (S_A)	8388	25,199	8191	41,778
Ceramic/Vitrified tiles (C_T)	36,408	81,541	25,584	143,533
Float Glass	3435	1650	4480	9565
Security Glass	0	52,860	0	52,860
Paint	11,360	23,840	11,282	46,482
Plywood	3647	52,883	2605	59,134
Total *EE* [MJ]	532,421	1,348,093	468,166	2,348,680

RESULTS AND DISCUSSION

As per scientific literature, the outcomes invariably depend on the *EW* and *EE* consumptions per unit area of the building's construction as per the following sub-sections.

Embodied water and energy consumption per unit construction area of the houses

Using total *EE* and *EW* consumptions of the aggregated and disaggregated cases from **Table 5** and **Table 6** and the respective total construction area, the consumptions are assessed per unit construction area basis. CJH-A represents the construction area of all the houses together. **Figure 3** illustrates the *EW* details. The relationship between *EW* and the covered area is not prominent in the three cases. However, for the nearly 250% covered area increase from CJH-1 to CJH-2, the *EW* value only increased to 20.78 kL/m^2 from 18.75 kL/m^2 (10% only).

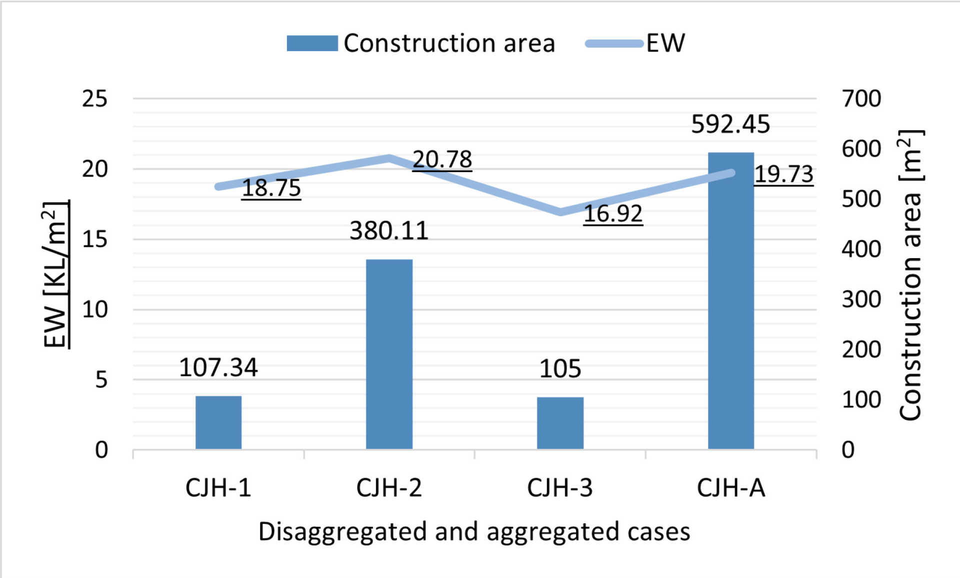

Figure 3. Relating embodied water to houses' construction area

At the same time, CJH-1 and CJH-2 are almost similar in area but differ in *EW* by an equal margin of 10%. Several underlying reasons exist, including the difference in finishes, the number of RCC slabs (FAR and the ground coverage) and the number of rooms. Nevertheless, a coherent relationship between the covered area and *EW* has not surfaced, as is evident in **Figure 3**.

CJH-A's *EW* is assessed at 19.73 kL/m^2. An Indian study finds 22.39 kL/m^2 for 27 materials taking 4 houses **[20]**. The first Indian *EW* study computed 25.60 kL/m^2 *EW*, but the very high EWC of steel considered in the study influenced the results, even though it considered only three top-used materials **[31]**. Another Indian study **[17]** covers 18 materials and finds 16.7 kL/m^2 *EW* under the joint impact of Indian and Australian **[27]** EWCs. A residential study from a water-scarce country finds only 3.34 kL/m^2, although it covered only three materials involving various typologies of different locations **[49]**. While the scope to conserve *EW* exists, quantitative comparisons do not make sense considering the above studies' holistic preview. Moreover, developed countries like Australia involve more machinery in production, while the Indian material industry is heavily dependent on humans. So, the unaccountability towards water use (UFW) in India also accounts for more *EW* consumption with more humans involved. Examining the chronology of top impacting parameters like material use is more sensible, as literature **[28]** also upholds.

Figure 4 details the *EE* consumption vis-à-vis the construction area of the houses individually as well as the aggregated one (CJH-A). The total *EE* values in MJ are sourced from **Table 6**, in addition to the construction area of respective or aggregated houses.

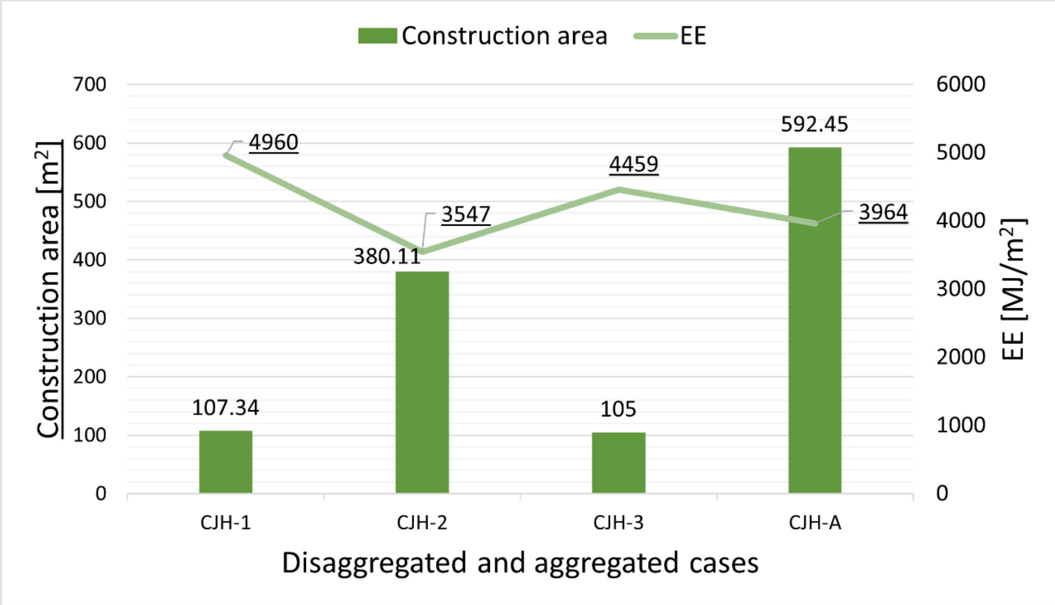

Figure 4. Variation in embodied energy to differing construction areas

CJH-2 is returning a lesser *EE* of 3547 MJ/m^2 compared to smaller residences, CJH-1 and CJH-2. As discussed, there are potential underlying reasons. *EE* per unit construction area in CJH-2 is reduced due to the distributed impact of high EE on the foundation, as CJH-2 is a two-floor construction. CJH-1 and CJH-3 involve single-storey construction only, while a greater number of walls and partitions accommodate the needs of a family similar in size to CJH-2. So, both the number of floors and walling material seem decisive. However, the *EE* vis-à-vis construction area pattern is far more apparent than the *EW* case.

CJH-A returns 3964 MJ/m^2 *EE*. As per the literature, a range of 3000 to 5000 MJ/m^2 stands outlined for the Indian context **[58]**. Other Indian studies find higher 7350 MJ/m^2 **[59]** and lesser 2092–4257 MJ/m^2 **[60]** *EE* values for different system boundaries and varied construction materials. A study using the native and Australian EEC observes it at 7158 MJ/m^2 **[28]** while evidencing nearly the exact chronology of top-impacting materials irrespective of the EECs used. Notwithstanding, prominent non-Indian studies [61–64] report a higher *EE* than Indian ones and translate that increased machine dependency on materials production overseas is counter-productive for *EE* regarding human-oriented Indian manufacturing. It leads to contemplating the impacts of the various materials on the *EE* or *EW* consumption per unit construction area. Then, it is feasible to have a material-to-material comparison concerning the respective percentage of *EE* or *EW* share in total consumption and work towards doing more with less, as SDG 11 encourages. The aggregate case (CJH-A) is only taken up as the representative of the cases analysed to see material-wise *EW* and *EE* impacts, thus compacting and simplifying the process,

Materials-wise embodied water and energy consumption

Figure 5 shows the material-wise *EW* consumption in CJH-A (**Table 5**, last column) and the total CJH-A *EW* consumption of 11,688.6 kL, expressed as a percentage, thus clarifying the entire picture for the *EW* component. Sand and stone aggregates top the impacts, followed by plywood, paint, and toughened glass. The result agrees with the latest Indian *EW* study **[17]**. Steel, cement and brick receded from the contention concerning other materials, contrary to the findings of another Indian study **[31]**, which did not consider other materials in the assessment. Thus, this study's significant system boundary is refining the *EW* research. Similarly, Figure 6 depicts the percentage material-wise *EE* consumption for CJH-A. The values are derived using the quantities in **Table 6**. The material-wise *EE* behaviour is observed to have reversed in relation to the *EW* behaviour. Brick, cement and steel impacts top the list, while others sway away significantly. The results align with the various *EE* studies [16, 58, 65]. A comparison between water and energy indexes indicates that the material-wise impacts are more distributed for *EW* consumption (Figure 5). At the same time, more than half of the materials seem insignificant in the case of *EE* (Figure 6). It is inevitable to see a material-wise comparison between *EE* and *EW*.

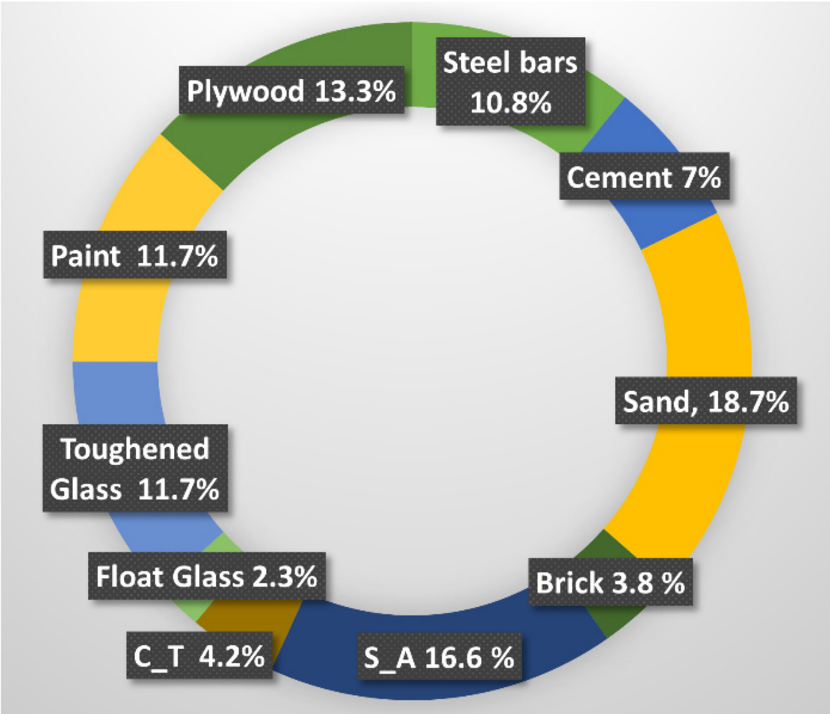

Figure 5. Percentages of material-wise embodied water contribution in the aggregated case

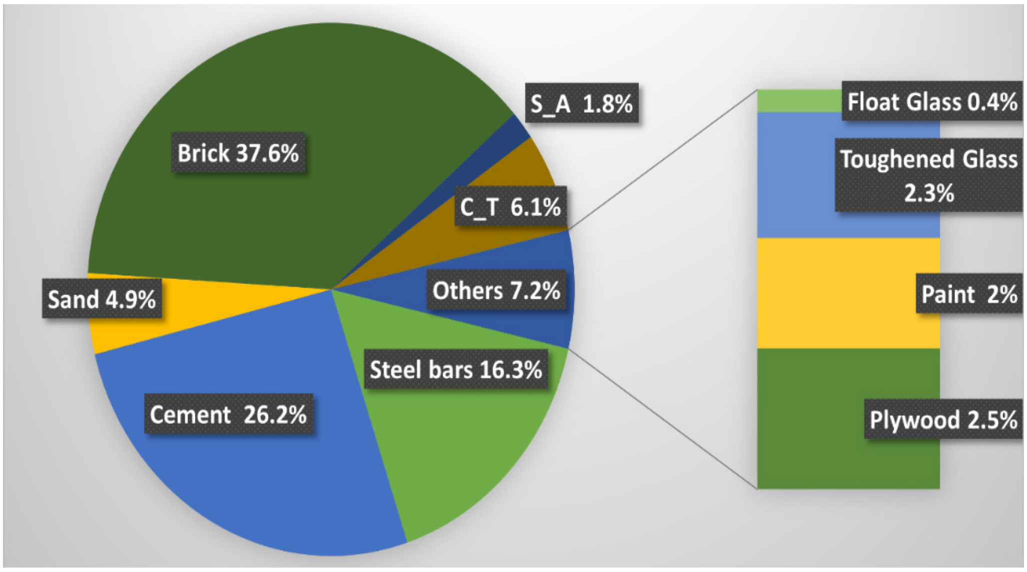

Figure 6. Percentages of material-wise embodied energy contribution in the aggregated case

Comparative materials-wise embodied water and energy consumption

Figure 7 illustrates the comparative percentage contribution of total materials in the aggregated case. All the materials are plotted along the horizontal axis. At the same time, the differentiated bars along the vertical axis show the percentage of material-wise *EW* and *EE* contributions for CJH-A.

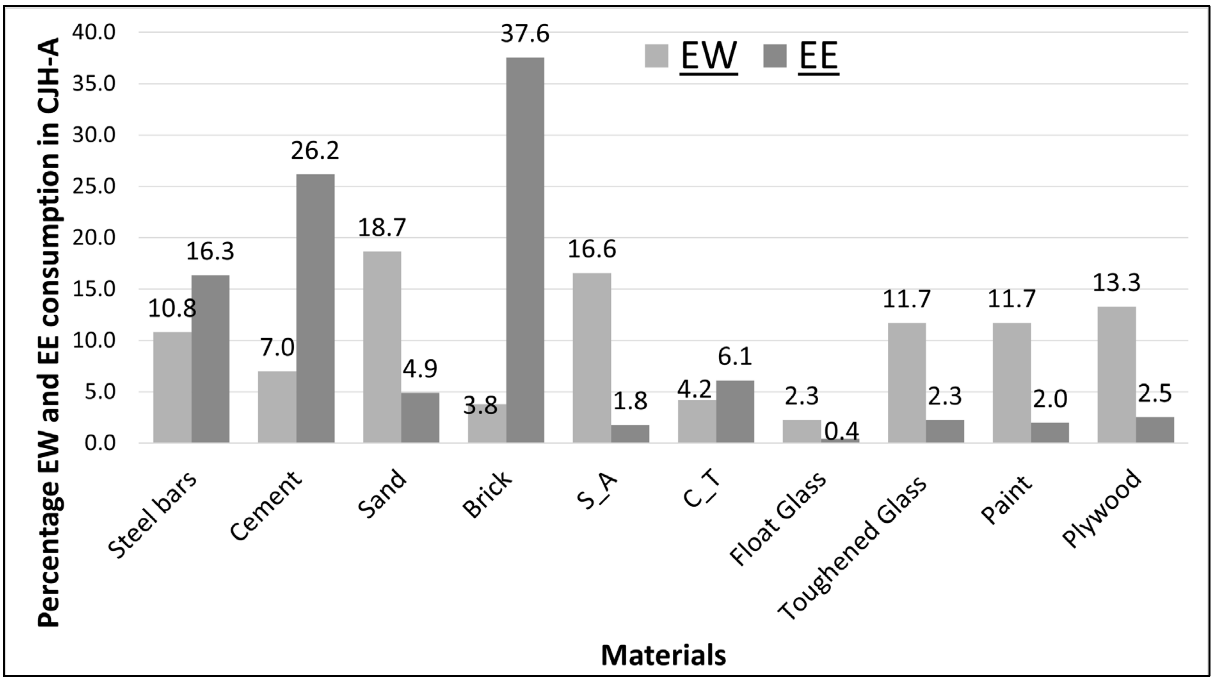

Figure 7. Comparative material-wise embodied water & energy contribution in the aggregated case

Figure 7 is a clear testament to the differential behaviour of materials in *EE* and *EW* parameters. For example, brick is the topmost *EE*-impacting material. However, it retards significantly from the top *EW*-impacting material. The outcomes create a hefty task because the preference for brick use is enormous among locals. The prolonged *EE* research has already contained *EE* significantly, but the *EW*-conscious approach involving high brick use might neutralise the *EE*-offsetting. So, finding the 'opportunity' in the 'threat' of high *EE*-laden brick use can be one of the design-decision guides. Cement shows a similar behaviour, too. On the other hand, toughened glass, paint, and plywood have significant *EW* impacts but are satisfactory in *EE* impacts, as per Figure 7. Sand and stone aggregates (S_A) also have a similar pattern. Steel dominates more in the *EE* aspect than *EW*. Using different methodologies, the proponents [40, 41] also discovered the weak and inverse *EW* to *EE* relationship at the material level, even at different locations. So, the argument remains that the efforts for *EE*-conscious buildings over the decades do not cover the *EW* domain appreciably. Hence, the efforts towards holistic sustainable construction seem lacking. Building construction players must ensue for a sustainable building solution that simultaneously conserves *EE* and *EW*.

To practice sustainability, the involvement of stakeholders and, specifically, the locals is extensively advocated for real-world applicability and success. Thus, to seek *EW* and *EE* conserving building solutions, it is essential to seek the stakeholders' choices first for optimum on-field implementation. The stakeholders, i.e. the building owners, are non-compromising towards a few aspects of the conventional houses while remaining flexible to fewer others. For this reason, this contribution only looks to intervene in conventional practices and not look for alternate solutions. Alternate solutions are potentially challenging for building owners to embrace owing to the prolongation of conventional practices, the availability of such materials/labour, and the ease of using and relating to them. However, not one but multiple materials and techniques are already in vogue for conventionally constructing various building elements. Hence, this exploration finds it more logical to assess the most appropriate existing construction method vis-à-vis *EW* or *EE* impacting one, indeed, with the evidence.

Building regulations in Jammu specify the ground coverage, setbacks and total construction area vis-à-vis the plot sizes of conventional houses. Conventional practices involved the preference towards wood-joinery (doors/window frames). However, its availability has whittled down its use. Mass boulders are the preferred way of constructing foundations. Most conventional house owners are flexible on finishes, structure systems (load bearing or composite or RCC frame), and foundations (mass boulders, stepped foundations in brick, or complete RCC foundations). Wood is not a preferred material in present times owing to cost, durability and availability in good quality. Plywood, toughened glass, and expansive paints are taking centre stage in the choices of contemporary house owners. It is worthwhile to mention that there is regular non-compliance with building regulations in most conventional houses, specifically in the city's fringe areas. Monitoring and reporting building regulations are getting stricter with time, and this is a welcoming move towards the real-world implementation of this study's purpose. However, all the choices above in building construction practices have a lot to do with the economic well-being of the house owner. For example, a middle-income group (MIG) house owner prefers 4–5 bedrooms despite a family size of 4 or 5. The high-income group (HIG) even surpasses that for the same family size and prefers the expansive finishes. At the same time, the lower income group (LIG) can afford only a bare minimum to start with his shelter and would add the rooms with time as per need and income growth. Literature finds evidence **[66]** of intervening in the building regulations for energy and water use; however, construction or material-specific modalities need deep regulatory insights. So, it is worth seeking insights and taking cognisance of the building bylaws and the owners' preferred choices vis-à-vis the family's economic status.

Scenarios creation

With the purpose of determining how future houses should be visioned to consume less *EE* and *EW* per unit construction area, a scenario creation exercise is taken up. Overall, the exercise tells us how using native methods and preferences can easily start offsetting *EE* and *EW* vis-à-vis current consumption as per the actual cases taken. Through detailed site visits of the authors involving discussions with 22 stakeholders of the study region, which involved four architects and several contractors/masons & house owners, various scenarios are devised to see their impacts on *EE* and *EW*. The scenario exercise is based on the observed impacts in previous sections vis-à-vis local building practices, locals' interests & issues and building regulations. As a result, the scenario conditions and resultant material estimates are generated by the assumptions provided by the consulting stakeholders, which are the local construction experts. The authors' familiarity with the conventional constructions and the preferences/challenges of the local community also benefit the entire exercise.

The aggregated case CJH-A is a base case in the scenario-building exercise. It is of utmost consideration in devising and shortlisting scenarios that most new constructions belong to LIG or MIG only, as this economic group is the principal constituent of Indian society. The scenarios devised are explained in **Table 7**, where the *EW* scenarios are abbreviated as SCJH-1 to 10 in addition to the 'original' scenario. The original scenario considers the material-wise consumptions in aggregated case (CJH-A) and corresponding *EE* and *EW* consumptions. Many other scenarios also emerged, but owing to significant unpragmatic considerations, they are done away with. While conditions for *EE* or *EW* scenarios are the same, *EE* scenarios are named for convenience by adding the suffix 'E' to the *EW* scenario names, as **Table 7** shows.

Table 7. Scenarios detail

Name of scenario	Detail of scenario
Original	All components bear original quantities for CJH-A. *EW* and *EE* consumption are 19.73 kL/m^2 and 3964 MJ/m^2 – composite structure system (with few RCC columns to support the roof and the load-bearing ceramic brick masonry walls). Mass boulder foundations beneath brick walls and RCC columns have isolated footing – no steel in plinth beams.
SCJH-1/SCJH-1E	Instead of paint, ceramic/vitrified tiles wall finishing in the interior and exterior. C_T increases by 400%, while paint decreases by 90%.
SCJH-2/ SCJH-2E	Against 'original', C_Area reduces by 20%, so steel decreases by 20%. Cement, sand, S_A, paint, and plywood decreased by 10%. Brick and C_T reduce by 15%. F_G and T_G also reduce by 5% compared to 'original'.
SCJH-3/ SCJH-3E	All walls bear exposed brick finish on internal and external faces, excluding the internal faces of the kitchen and toilet walls. The original wall thicknesses are retained. Cement, sand, and paint reduce by 25%, 30%, and 90%, respectively. Rest remains unchanged.
SCJH-4/ SCJH-4E	Exposed brick masonry, load-bearing construction in totality and brick foundations. Steel and cement were reduced by 25% compared to the original case. Sand and S_A were reduced by 35%. Brick use increases by 20%, while paint decreases by 90%.
SCJH-5/ SCJH-5E	In addition to SCJH-4 conditions, C_Area reduces by 20%. So steel reduces further by 20%. Cement, sand, paint, plywood, and S_A reduce by 10% compared to SCJH-4. Brick and C_T reduce by 15% compared to SCJH-4. F_G and T_G reduce by 5% compared to SCJH-4.
SCJH-6/ SCJH-6E	In addition to SCJH-5 conditions, Maximise T_G discouragement (90% reduction), including total discarding of the glass railings. Conventional metal railings are used. Plywood reduces by 75% as the scenario considers movable metal cupboards. Using F_G with wooden frames increases F_G by 50%. The paint stays unchanged as SCJH-5.
SCJH-7/ SCJH-7E	In 'original', brick masonry is entirely removed by concrete blocks. The external faces of the outer walls are not plastered, while cement plastering is applied on 1/4 of the remaining walls. So, bricks reduce by 90%, paint by 50%. Cement and sand use increased by 12% and 25%, respectively. S_A increased by 25% compared to 'original'.
SCJH-8/ SCJH-8E	In the original scenario, half of the brick masonry is replaced with concrete bricks. All the brick and concrete brick masonry is laid in rat-trap bond without cement plaster. Bricks reduce by 62%. Cement and sand use increased by 5% and 10% to 'original'. Composite construction is retained. S_A use increases by 15%. T_G and plywood use are discouraged and reduced by 90% and 75%, respectively. F_G use increases by 50%. Paint reduces by 90%. The rest remains the same as the 'original'.
SCJH-9/ SCJH-9E	Concerning SCJH-3, the rat-trap bond is introduced, and T_G partitions replace most interior brick walls. Brick use decreased by 80%, while cement and sand were reduced by 33% and 40% to the original scenario. Paint remains at 10% of 'original' (overall plastering is removed). Approximately 300 m^2 (or 5986.41 kg) of T_G adds up, having an EWC=15.48 kL/m^2 and EEC=30 MJ/kg. Rest remains unchanged.
SCJH-10/SCJH-10E	C_Area reduces by 20% than SCJH-9. Steel and T_G are reduced by 20% – a reduction of 10% each in cement, sand, S_A, paint, and plywood. Brick and C_T reduce by 15%. F_G reduces by 5%.

Analysis using scenario manager

Table 8 summarises the *EW* scenario manager summary as generated through the decisions of the survey with the local construction players. There are, in total, 11 scenarios (original plus 10) where all the material quantities are assumed on the set of pre-requisite conditions devised, as explained in **Table 7**. The larger purpose is to seek the best-fitting *EW* conserving scenario and re-assess the conditions for further onsite implementation through policy and onsite reforms. The vertical columns explain the scenarios, while the horizontal rows depict each scenario's materials-wise *EW* quantity [kL]. The construction area of the aggregated case (C_Area) is also shown in a row towards the bottom half of the table. Concerning the inputs of material-wise *EW* quantities [kL] and C_Area [m^2], the output in *EW* per unit construction area [kL/m^2] is assessed using the scenario manager technique and reflected in the last row of **Table 8**. The scenario manager also provides the overall summary explaining the inputs and outputs of all the scenarios, as **Table 8** illustrates. For better comprehension, all the inputs and outputs are demarcated in distinguished colours, showing their comparison, i.e., higher, equal or lesser to the original scenario values, as per the index provided at the bottom.

Table 8. Inputs and outputs of embodied water scenarios

	Scenario										
	Original	SC JH-1	SC JH-2	SC JH-3	SC JH-4	SC JH-5	SC JH-6	SC JH-7	SC JH-8	SC JH-9	SC JH-10
Inputs: Material-wise *EW* [kL] for CJH-A											
Steel	1262	1262	1009	1262	946	757	757	1262	1262	1262	1009
Cement	818	818	736	613	613	552	552	916	859	548	493
Sand	2181	2181	1963	1527	1418	1418	1418	2727	2399	1309	1178
Brick	444	444	377	444	532	452	452	44	169	89	75
S_A	1937	1937	1744	1937	1259	1133	1133	2422	2228	1937	1744
C_T	490	2451	417	490	490	417	417	490	490	490	417
F_G	266	266	252	266	266	252	378	266	398	266	252
T_G	1367	1367	1299	1367	1367	1299	130	1367	137	6011	4808
Paint	1370	137	1233	137	137	123	123	685	137	137	123
Plywood	1555	1555	1399	1555	1555	1399	350	1555	389	1555	1399
C_Area [m^2]	592.5	592.5	474	592.5	592.5	474	474	592.5	592.5	592.5	474
Output: Scenario-wise total *EW* per unit construction area											
EW [kL/m^2]	19.73	20.96	22.00	16.20	14.49	16.46	12.05	19.80	14.29	22.96	24.26
'<' original scenario				'>' original scenario				'=' original scenario			

Like **Table 8**, **Table 9** and **10** illustrate the inputs and outputs summary detail of *EE* scenarios, using the details of **Table 7**. In **Table 8** and combined **Tables 9** and **10**, five scenarios return less *EW* than the base case with a minimum of 12.05 kL/m^2 for SCJH-6, corresponding to 39% *EW* offsetting. On the other hand, eight scenarios reflect conservation in *EE* compared to the CHJ-A, with the minimum being 2586.1 MJ/m^2, i.e., an *EE* saving of 35% (SCJH-9E). However, both the best-performing scenarios are different, and so are the worst-performing ones, too. It is an impending proof that:

- *EW* and *EE* are not positively or directly correlated with each other.

A few proponents [21, 34] also predict the inverse *EW-EE* relationship. Both SCJH-2 and SCJH-2E involve C_Area reduction by 20% but also return higher *EW* and *EE* than the 'original' case. Both scenarios require a reduction in every material. However, the corresponding decrease in C_Area (denominator) compensates for the reduction of the materials (numerator) and returns higher *EW* and *EE* per unit construction area. It implies:

- Area reduction alone cannot check *EE* and *EW* per unit construction area unless other concurrent measures exist.

Table 9. Detailing the inputs and outputs of embodied energy scenarios – part 1 (scenarios SC JH-1E to SC JH-5E)

	Scenario					
	Original	SC JH-1E	SC JH-2E	SC JH-3E	SC JH-4E	SC JH-5E
	Inputs: Material-wise *EE* quantity [MJ] for CJH-A					
Steel	384,000	384,000	307,200	384,000	288,000	230,400
Cement	614,400	614,400	552,960	460,800	460,800	414,720
Sand	114,929	114,929	103,436	80,450	74,704	67,234
Brick	882,000	882,000	749,700	882,000	1,058,400	899,640
S_A	41,778	41,778	37,600	41,778	27,156	24,440
C_T	143,533	717,664	122,003	143,533	143,533	122,003
F_G	9565	9565	9087	9565	9565	9087
T_G	52,860	52,860	50,217	52,860	52,860	50,217
Paint	46,482	4648	41,833	4648	4648	4183
Plywood	59,134	59,134	53,220	59,134	59,134	53,220
C_Area [m^2]	592.5	592.5	474	592.5	592.5	474
	Output: Scenario-wise total *EE* per unit construction area					
EE [MJ/m^2]	3964.4	4862.8	4277.3	3576.3	3677.6	3956.3
‘<’ original scenario	(green)	‘>’ original scenario	(red)	‘=’ original scenario	(cyan)	

Table 10. Detailing the inputs and outputs of embodied energy scenarios – part 2 (scenarios SC JH-6E to SC JH-10E)

	Scenario					
	Original	SC JH-6E	SC JH-7E	SC JH-8E	SC JH-9E	SC JH-10E
	Inputs: Material-wise *EE* quantity [MJ] for CJH-A					
Steel	384,000	230,400	384,000	384,000	384,000	307,200
Cement	614,400	414,720	688,128	645,120	411,648	370,483
Sand	114,929	67,234	143,661	126,422	68,958	62,062
Brick	882,000	899,640	88,200	335,160	176,400	149,940
S_A	41,778	24,440	52,222	48,044	41,778	37,600
C_T	143,533	122,003	143,533	143,533	143,533	122,003
F_G	9565	13,631	9565	14,348	9565	9087
T_G	52,860	5022	52860	5286	232,452	185,962
Paint	46,482	4183	23,241	4648	4648	4183
Plywood	59,134	13,305	59,134	14,783	59,134	53,220
C_Area [m^2]	592.5	474	592.5	592.5	592.5	474
	Output: Scenario-wise total *EE* per unit construction area					
EE [MJ/m^2]	3964.4	3786.4	2775.8	2905.5	2586.1	2746.5
‘<’ original scenario	(green)	‘>’ original scenario	(red)	‘=’ original scenario	(cyan)	

So, it concludes that *EE* conservation measures over the decades have yet to sufficiently check *EW* in parallel, as suggested by a few preceding studies [34, 41]. A special effort is an eminent requirement to contain *EE* and *EW* simultaneously through *EE-EW* nexus studies on building construction. A comparative picture of the scenarios devised is plotted in **Figure 8**. All scenarios except the original are concisely abbreviated for the same convenience. For example, scenarios SCJH-1 or SCJH-1E are represented as one (1), and a similar approach for other scenarios is also taken. **Figure 8** contains the original plus ten scenarios devised for the aggregated case (as already detailed in **Table 7**) along the horizontal axis. At the same time, *EE* [MJ/m^2] and *EW* [kL/m^2] are plotted along the primary and secondary vertical axes in the tornado plot. The distinction of the impacts using colours clarifies the meaning in **Figure 8**. As it reflects, the vertical bars are for *EE* while the graph line represents *EW*. The horizontal axis is shifted (red) to intercept the primary vertical axis *EE* reading of the original scenario (3964 MJ/m^2). It simplifies scenario distinction, which returns more or less *EE* quantity than the original scenario plus the corresponding *EW* quantity from the secondary vertical axis in **Figure 8**.

This figure distinctively illustrates two scenarios (1 and 2) with more *EE* than the original scenario through the two bars (green) on the upper side of the shifted horizontal axis (red). Scenario 1 reports the highest *EE* but not the highest *EW*, while the lowest *EW* rests with scenario 6 (12.1 kL/m^2) but does not return minimum *EE*, which strongly points to a non-relationship between *EW* and *EE*. Similar reflections are also in scenarios 9 (minimum *EE* but not minimum *EW*) and 10 (highest *EW* but not highest *EE*). So, the non-positive relationship between *EE* and *EW* is potentially corroborated. However, among the eight scenarios on the lower side of the horizontal axis returning lesser *EE* than the original scenario, three scenarios (7, 9 and 10) still report higher *EW* vis-à-vis the original scenario. Such a reflection indicates the reverse behaviour of *EE* and *EW* in building construction, as also hinted by various proponents [21, 28, 39] before.

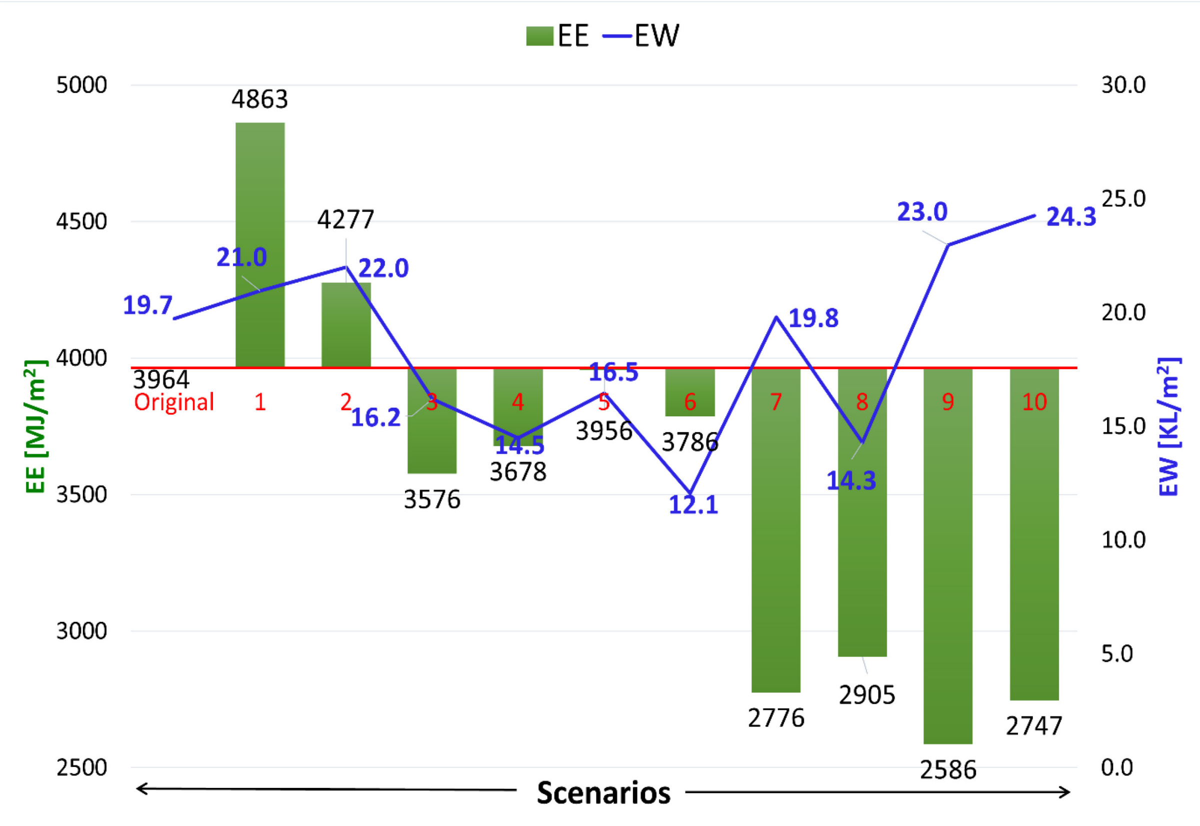

Figure 8. Tornado plot illustrating the summary output of embodied water-energy nexus scenarios

A few scenarios, like scenario 8, do keep the hopes alive that exceptions are possible with legible policy and A+D interventions. So, the interpretations of the comparative *EE* and *EW* scenarios (**Figure 8**) lead to the following:

- The best-performing *EW* scenario 6 reports 12.1 kL/m^2 *EW* in the aggregated case and conserves 39% vis-à-vis the original scenario. However, only a tiny fraction, 4.5%, of *EE* conservation is found; the reported *EE* result is 3786 MJ/m^2.
- The second-best-performing *EW* scenario 8 reports 14.3 kL/m^2 *EW*, a reduction of 27.5% vis-à-vis the original scenario. *EE* reduction is 27% compared to the 'original' with an *EE* report of 2905 MJ/m^2.
- Other *EW* scenarios like 4, 3, and 5 report much higher *EE* and *EW* values than scenario 8.
- The best-performing *EE* scenarios 9, 10, and 7 report only a fraction of *EE* offsetting compared to scenario 8, in addition to considerably escalating *EW*.

Observing also that scenarios 3, 4, 5, 6, and 8 return less *EW* and *EE* than the original, it is essential to highlight the corresponding architecture plus design (A+D) and policy interventions devised. Indeed, the said scenarios uphold the hypothesis of the study. The decision-making at various stakeholder levels must be outlined to consolidate the evidence further.

Design decisions and regulatory insights

Appendix Tables A1 and A2 outline the roles of multiple stakeholders, including the A+D team and policy governance. As discussed, top-performing scenarios 8 and 3, 4, 5, and 6 are considered for devising those tables' recommendations. The tables illustrate that no scenario from **Table 7** or **Figure 8** meets the high-income group (HIG). Because the conventional constructions happening in Jammu predominantly belong to the middle-income group (MIG) and lower-income group (LIG). Moreover, the regions under stress because of the rapid rise in conventional houses are the peripheral regions of Indian cities like Jammu, and HIGs seldom prefer such locations. So, resource conservation issues are more dictated by MIGs and LIGs. However, in the implementation of scenarios, HIGs can be potential deterrents in real-world applications and can significantly overshadow the reforms in LIGs and MIGs. Thus, **Table A1** and **Table A2** recommendations precisely include HIGs too. Some crucial recommendations secured by the site experiences and local experts call for avoiding cellar construction by HIGs and upper MIGs. **Table A1** and **Table A2** recommendations base is flexible and coupled with penalties and incentives if required.

Both mentioned **tables** outline the section-wise societal preferences for house construction, A+D and policy decisions required to combat *EE* and *EW*. As discussed, SCJH-8 best fits the *EE* and *EW* conservation, and its assumptions (**Table 7**) best cater for the MIGs. It returns *EE* and *EW* offsetting by a minimum of 27% each concerning the base case. While SCJH-6 fits the LIGs best, it is also crucial, as most conventional houses belong to LIGs. It conserves *EW* by 39% minimum vis-à-vis the base case. As per **Figure 8**, *EE* saving is very little; however, given the *EE* conservation focus for many decades, buildings are already *EE* conscious. So, it is time to focus on *EW*, and SCJH-6 seems fitting for MIGs, too. Meanwhile, the reduction is inevitable in SCJH-6 and SCJH-8 if best practices from scenarios 3, 4, 5, 6, and 8 are carefully added.

The significant role of concrete **[67]** and steel **[68]** in *EW* consumption was previously observed by many proponents, including a recent UAE-Villa-based study **[69]**. However, interestingly, all the favourable *EE*-*EW*-conscious scenarios signify playing with the bricks in one way or another. Such scenarios solutions also vouch for replacing mass boulders foundations with brick foundations and coherently meet not just *EW* but also retards the high lifecycle carbon emissions associated with the steel or concrete structure system **[70]**. The observation is a breakthrough validation to outline the pragmatic nature of insights discovered. Brick use dominates the rest of the materials in *EE* (**Figure 7**); however, it is the most preferred material among locals. The solutions recommend continuing brick use with intelligent tweaks, which upholds the 'opportunity' in the 'threat' of local-centric building practice as anticipated in the previous sections. So, a high acceptance rate for the solutions is inevitable. As indicated in **Table A1** and **Table A2**, certain A+D and policy recommendations can also reduce *EE* and *EW* during the construction and other lifecycle phases. For example – intelligent brick use avoids several finishes, which otherwise have a high *EW* impact **[19, 69]** and finishing materials account for 47% of the recurrent *EW* (maintenance phase of buildings) **[69]**. Knowing that water wastages are more than 80% **[20, 23]** directly or indirectly through human activities, minimising finishes also saves water, site personnel and construction duration. So, lifecycle impacts can bear further reduction when more and more phases of cradle-to-grave life cycle assessment are performed prospectively using the bottom-up approach.

Scenario 8 (or SCJH-8/SCJH-8E) is the best-fitting scenario per this study's scope. The study provides the quantities of *EW* and *EE* per unit construction area for the houses while also enlisting dominant *EW*- and *EE*-impacting materials. Thus, the study can be a base for the knowledge audience to seek *EW* and *EE* conserving construction solutions through various scenarios through the methodology illustrated in this study. Probably, a more significant number of cases, more materials and differing base cases can return improvised solutions quantitatively. Simultaneously, more iterations or improvised methods, like building information modelling (BIM) or simulation-based iterations, are inevitable. Nevertheless, *EW*-*EE* nexus studies through partnerships of water and energy researchers are the key to holistic, sustainable communities.

Solutions catering for the interdependency of energy-carbon emissions or energy-water are currently highly sought after **[72]**. However, for the building construction sector, it is indeed novel to contemplate the simultaneous consideration of *EW* and *EE*. The fact that the experiment outlined that intelligent *EW* combating measures can also offset *EE* is a novel and contrasting finding to the literature bank **[29, 41]**. **Table A1** and **Table A2** insights also help uphold the hypothesis and assure the aim while finding a legible way to transform 'threat' into 'opportunity' by embracing local strengths like brick use. Never before has any study outlined the *EW* & *EE* offsetting solutions with evidence emerging from the locals' preferences, local economic level, and local construction players. The A+D interventions and corresponding policy insights are unprecedented in securing highly pragmatic outcomes. Further, it has emerged that offsetting *EW* is the need of the hour vis-à-vis consolidated *EE* research.

The implications possess tremendous worth in meeting sustainable development goals like SDGs 6, 11, 12, and 17. As the Indian construction sector is vital to determine the impact of global construction, India's commitment to achieving net zero emissions by 2070 should get a healthy boost from the current initiative. The study not only emphasises the *EW* research domain but also, through the representation of the *EW*-*EE* nexus and the inability of *EE*-conscious buildings to automatically ensure *EW* conservation, is the fitting outcome for the knowledgeable audience. *EW* is critical in practising building-level sustainable solutions in the water-conscious world. At the same time, the fact that the study also presented a methodology to assess *EW* under the present state of the art is a generous takeaway of this scientific contribution. The study has a lasting potential to be replicated across contexts and regions; however, it invites constant methodological changes to suit the contexts. As it stands, *EW* research needs an intensive effort having prominence nothing short of *EE* if we are to ensure progress towards building constructions' ideal sustainability.

CONCLUSIONS

The current investigation follows a bottom-up methodology involving three conventional houses in Jammu, India, and seeks energy- and water-efficient construction based on the *EW*-*EE* nexus. The methodology uses a database of ten building materials and is novel in prioritising localised wisdom through the scenario manager technique. The experiment advances to coalesce A+D measures and locals-centric policy decisions to achieve fitting *EW*-*EE* conserving scenarios. Observing different sets of top impacting *EW* materials to *EE*, the initial results uphold that *EE* offsetting is a deficit to conserve *EW* unless special measures are adopted. Instead of consolidating the inverse and weak *EW-EE* interrelationship, the analyses divulge deeper and could reflect how to combat *EW* and *EE* simultaneously, with high real-world applicability. The scenario manager outlined an *EW* reduction of up to 39%, while a joint *EW-EE* conservation of 27% is evidently achieved. Besides illustrating the policy insights and A+D interventions conducive to dominant societal economic groups, the outcomes transformed the 'threats' of localised practices into potential 'opportunities' with intelligent tweaks.

Nevertheless, the locals remained in the limelight regarding the scenarios and the discovered insights. Because of the locals-centric nature, the insights have a high degree of adaptability by the locals and could overcome the reasons for poor field applications of sustainable building practices. The experiment advances the predecessors as it caters to the environmental (*EW* and *EE*), socio-cultural (conventional houses and localised practices & material only) and economic (MIGs and LIGs) aspects of sustainability.

The study involved three conventional houses and an inventory of 10 materials, so advanced boundary conditions and houses can reflect improvised outcomes. Indeed, the literature speaks for underestimations involved in bottom-up approaches, so the study might not have wholly unravelled the adverse reality. Also, it is intriguing to seek different building typologies for *EW-EE* nexus-based interventions. The current research outlined the nexus for cradle-to-gate phase LCA only, so considering other phases of LCA in cradle-to-grave assessments interests the current and prospective building researchers. The prospective research can further the methodology support to propose alternate practices as per the context. Through future studies, multiple iterations based on tools like BIM and any simulation platform are inevitable and can advance the current results. The economic viability of the solutions is another dimension to ponder to further the buildings' sustainability outreach.

Indeed, the study is a precious contribution to the scarce *EW* domain and a valuable one attempting *EW-EE* nexus for building construction. Because of dynamic databases, it is not the quantitative comparisons but the top-impacting materials and policy decisions that are the key takeaways. The focus on *EW* requires a different approach to the ongoing *EE* reforms, which is an invaluable outcome and needs to be emphasised vis-à-vis *EE* in order to practice the environmental sustainability of constructions. The results, the methodology and the discussion are highly replicable across regions and stimulate the world of academia and profession. The remedial measures are inevitable and can be as small as the metering of the consumptions (especially water in construction materials production and use) in Jammu smart city and other thoughtful developments across regions, but beginnings are vital. The future sustainability debate of building construction cannot afford to leave the *EW* agenda unattended, specifically in the current thirsty world.

ACKNOWLEDGMENT(S)

The authors acknowledge the support of IIT Roorkee and SMVD University, Katra (J&K) in the research. The financial support provided by the Indian Council of Social Sciences Research (grant no. CON/164/2024-25-ICS) and Dean of Resources and Alumni Affairs (DORA), IIT Roorkee (grant no. IITR/GIC-56/2024/06) towards attending the 19^{th} SDEWES conference in Rome are instrumental to this scientific contribution. All the authors remain highly grateful for the constructive feedback received from the reviewers and the editor during the review process.

NOMENCLATURE

EE	Embodied energy	[MJ]
EW	Embodied water	[kL]
Q	Quantity of the material	[FU]

Greek letters

α	Embodied water coefficient	[kL/FU]
β	Embodied energy coefficient	[MJ/FU]

Subscripts

i, j	Index of materials or group of materials

Abbreviations

A+D	Architecture plus Design
BIM	Building Information Modelling
EEC	*EE* Coefficient
EWC	*EW* Coefficient
EPiC	Environmental Performance in Construction
FAR	Floor Area Ratio
FU	Functional Unit (in this study, ton or m^2)
I-O	Input-Output (name of a method)
LC	Life Cycle
LCA	Life Cycle Assessment
RCC	Reinforced Cement Concrete
SBE	Sustainable Built Environment
SDG	Sustainable Development Goals
UFW	Unaccounted for Water Use
VW	Virtual Water
WF	Water Footprint

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APPENDIX

Table A1. Design & regulatory insights to jointly offset embodied water & energy, part 1

Societal section and preferences	A+D intervention	Policy and bye-laws intervention	Fitting scen-arios
HIG - Plot size (greater than or equal to 450 m^2) - More construction area 350 m^2 and above) and height (G+2) - RCC frame structure - Expansive finishes - Grand spaces - Cellar	- Have a larger construction footprint. Only G+1 construction with first floor covered area up to 40% of the ground floor. The need for columns and beams is reduced (RCC). The slab casting period is also optimised. - No need for raft foundation. - Reduce masonry walls to the maximum. Adopt Open plans and cut-outs (double-height spaces) in design. - All the masonry walls to be 115 mm thick. Wherever required, 230 mm thick walls will be laid in rat-trap bond. - Use adhesives for C_tile flooring and walling (cement and sand are reduced). - Marble stone, wherever used in flooring, can be used with adhesives or metal channels. - Do not use brick coba for floor sub-base.	- Up to 75% ground coverage to reduce floors (RCC component) and a maximum of two floors. - Have either first floor or cellar. - Have at most four rooms, including three bedrooms. - Exposed brickwork or exposed concrete work in masonry. - Toughened glass is discarded. - Minimise paintwork and plywood use. - No need for RCC sill bands and lintel bands. - Promote resource-efficient brick manufacturing in Jammu with transparent declaration of water and energy use in production. - Ensure all water used in construction is revenue water—no borewells are to be constructed onsite during or before construction. - Provide incentives if: a) Covered area is less than 275 m^2 or FAR is less than 0.7. b) Cellar is not constructed. c) At least 25% of the site area is kept green. d) Rainwater harvesting and an internal courtyard are provided	NA
MIG	- Discard the use of paint in masonry work throughout.	- Up to 60% ground coverage to reduce RCC and construction period.	SCJH-8 or

- Plot size (equal to or greater than 175 but less than 450 m^2) - More construction area 200-300 m^2 and above) and minimum height (G+1) - RCC frame or composite structure - Range of finishes - Multiple rooms - Cellar (at times)	- Use exposed or concrete bricks in material-saving masonry bonds like rat-trap bonds. Wherever finishing is required, use C_T with adhesives or metal grids. Cement, sand and paint remain in check henceforth. - The composite structure system is best, if not a pure load-bearing construction system, and should use RCC columns only at strategic locations. Need for RCC foundation for the walls. - Discard toughened (security) glass in totality, specifically in railings. - Avoid using plywood and related materials (board/veneer) in cupboards and decoration purposes in the interiors to the maximum extent. - Wood continues to be discarded during house construction.	- No cellar allowed. - Have a minimum of masonry work in the interiors. - Exposed masonry is mandatory. However, flooring material is allowed to be C_T or marble stone. - Toughened glass is minimal except for the large and trendy fenestrations. - Discard paintwork while keeping plywood use to a minimum. - Provide RCC lintel bands only if RCC plinth beams don't exist. There is no need for sill bands for low-rise tiny houses. - Provide incentives if : a) Covered area is less than 200 m^2 or FAR is less than 0.7. b) At least 30% of the site area is kept green. c) Rainwater harvesting and an internal courtyard are provided. d) Heavy monetary penalty for cellar construction and reduced FAR.	SCJH-8E

Table A2. Design & regulatory insights to jointly offset embodied water & energy, part 2

Societal section and preferences	A+D intervention	Policy and bye-laws intervention	Fitting scen-arios
LIG - Plot size (less than 175 m^2) - Phased construction of floors. - Construction area up to 100-200 m^2 and max. height (G+2) after some years of initial construction - Composite construction - Minimum finishes - Multiple rooms to accommodate a large family of 5-6 family members	- Minimum construction area. - Have exposed brick masonry in rat-trap bond to the maximum. - No use of T_G. - Minimum or no use of plywood/similar products. - Use load-bearing masonry throughout with brick foundations. - No use of RCC beams - Maximise single floor constructions. - No paint or expansive finishes. - Metal railings to be used in parapets instead of brick parapets. - C_T, Indian patent stone (IPS) or marble stone flooring.	- Have a minimum number of rooms to minimise masonry work. - Flexibility of having up to 70–90% of ground coverage. - No compulsion to use RCC components other than slabs. - Conserve sand and S_A using exposed masonry, brick foundations, load-bearing structure, adhesives/metal rails to fix C_T and similar interventions. - Provide incentives if : a) Covered area is less than 90 m^2 or FAR is less than 0.7. b) At least 20% of the site area is green or open to the sky. c) Rainwater harvesting and an internal courtyard are provided.	SCJH-6 or SCJH-6E

Paper submitted: 02.12.2024
Paper revised: 08.04.2025
Paper accepted: 08.04.2025