Environmental Impact Balance of Building Structures and Substitution Effect of Wood Structure in Taiwan

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Abstract- **Energy consumption and CO_2 emissions of building materials are examples of the perhaps most basic problems in construction sector for the built-environment. In this paper life cycle assessment (LCA) method is applied to the analysis of building structures (reinforced concrete structure, steel structure and wood structure) in Taiwan. This paper first discusses environmental burdens of reinforced concrete structure, wood structure and steel structure in Taiwan from cradle to gate perspectives. Secondly, material recovery strategy is adopted for analysing the balance of environmental impacts of structures in terms of embodied energy consumption and embodied CO_2 emissions. The influential factors for assessing quantitative results include material extraction, manufacturing process, transportation and recovery phase. The outcomes show that wood structure has highly environmentally friendly potential than that reinforced concrete and steel structures from cradle to gate perspectives and, further, if recovery strategy is taken, wood structure still has the lowest environmental impacts in Taiwan.**

Keywords- Life Cycle; Embodied Energy; Embodied CO_2; Material Recovery, Wood Structure

I. INTRODUCTION

As issues of climate change related to global warming are addressed, much attention is paid to the energy consumption and greenhouse gas emissions. Environmental life cycle assessment (LCA) can be defined as the compilation and evaluation of material and energy consumption as well as the potential environmental impacts of these through the life cycle of materials. ISO 14040 [1] defined LCA as: a technique for assessing the potential environmental aspects associated with a product or service by compiling environmental burdens associated with inputs and outputs and interpreting the results of the inventory and impact phases in relation to the objectives of the study. Besides, LCA is a technique to assess environmental impacts associated with all stages of a product's life from cradle to gate, to grave or to cradle perspectives. Life cycle impacts of a building have been widely investigated [2-4], and in order to understand the whole environmental impacts, embodied energy consumption and CO_2 emissions should include the material extraction, manufacturing, transportation, construction activities, dismantling operations and the end-of-life of the materials.

However, less attention is paid to the environmental impacts of material and energy recovery combined in the system boundary of life cycle in the analysis. It aims to recover as much of the economic and ecological value of materials, to therefore reduce the amount of waste at the end of material's lifecycle as well as to avoid or at least reduce the rate of the depletion of resources. The goal of sustainable construction should be considered for closed-loop material flows, i.e. recovering deconstructed materials so that materials collected at the end of life of a building which can then be linked back into material flow in the same or different condition and functionality after recovery [5]. In some way, material recovery indicates reduction of the embodied energy of original materials during the reuse and recycling process of materials. Energy consumption can be recovered by recycling process and environmental impacts are therefore lessened [6].

Wood is generally regarded as green material because it is the most common renewable resource in the world. Besides, carbon dioxide is absorbed during plant growing process, and when wood is manufactured into products, carbon is stored in the products for a long time. Even when the wood is combusted, combustion obtained from well-managed forests is assumed to have zero emissions because of the amount of CO_2 released during burning is balanced by CO_2 absorbed during forest growth. Thus, using wood to substitute for other materials of high intensive fossil-fuel consumption can reduce the environmental burdens.

As for building construction, it has been widely investigated that benefits of using wood structure includes low embodied energy consumption and low embodied CO_2 emissions in manufacturing process compared with other materials. Koch [7] who used USA data from 1970s and Buchanan and Honey [8] who used New Zealand data from 1980s calculated energy use and CO_2 emissions , discovering that environmental impacts are lower if wood material is used for building construction. More recently, CORRIM found two wooden houses that have lower embodied energy and global warming potential than equivalent design made of steel and concrete [9]. In addition, some reports have quantified ranges of possible use and CO_2 emissions from the manufacture or lifecycle of building materials, considering various aspects of lifecycle dynamics. Bojesson and Gustavsson [10] quantified the effects of land use and end of life changes of materials and concluded that wood-framed buildings have lower energy use and GHGs emissions than concrete-framed building. Peterson and Solberg [11] found wood construction to result in lower greenhouse gas emissions than non-wood material, with the amount depending on material waste management and how forest carbon flows are considered. In Taiwan, it has been discovered than reinforced concrete and steel structure consume greater amount of energy, 4.2 times more and 3.5 times more than wood structure [12].

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Due to the characteristics of environmentally friendliness of wood, wood substitution effect has thus aroused great concern in building sector. Schulz [13] proposed that substitution of wood by other materials and energy sources, which is continuing until today, will be reversed and a new perspective of re-introducing that wood start to environmental reasons and exhaustion of certain non-renewable materials and fuels. However, wood substitution is strongly related to competition with other materials. Generally speaking, the most important materials competing with wood are plastic, aluminium, steel, concrete and gypsum [14]. It has been suggested that wood elements could replace other competing products in main structure and interior works in Switzerland [15]. For instance, 2-layered brick can be replaced by laminated timber board for wall; steel pillar can be replaced by glued laminated pillar and interior plasterwork can be replaced by profiled board and so on. The issue of wood substitution is complicated simply because many factors will affect the use of wood not only in construction sector but also in consumer's behaviour, such as relative price, political and global drivers, social-economic factors, quality of material and local legislation [16]. But in this paper, only factors of environmental impacts of building structures are analysed in terms of energy consumption and CO_2 emissions.

As mentioned above, in Taiwan, Tu [12] has discovered that wood structure has great potential for our environment but data of wood manufacturing is focused locally in Taiwan; however, a great amount of wood is imported from North America. As a result, environmental impacts of long journey of wood transportation cannot be ignored. Besides, the source of iron ore is also imported from the west of Australia and then manufactured into steel products in Taiwan, thus some possible factors, for example, road and marine transportation, should be taken into account.

This paper aims first to investigate environmental impacts of reinforced concrete (RC) structure, wood structure and steel structure in terms of embodied energy consumption and embodied CO_2 emissions from a 'cradle to gate' perspective in Taiwan. And further, we extend its system boundary of life cycle to the phase of material recovery and energy recovery in order to analyse how environmental burdens can be offset by recovery strategy (life cycle balance). Besides, beyond the conceptual understanding of the environmental benefits of wood substitution, there is a need for quantitative analysis of greenhouse gas reduction and energy consumption reduction. A displacement factor (DF) for the substitution effect of wood structure has been developed to measure the amount of greenhouse gas (GHG) emissions and energy consumption which can be avoided when wood structure is applied in building construction instead of steel structure and RC structure.

II. METHODOLOGY, SYSTEM BOUNDARY AND ASSUMPTIONS

A. System Boundary

We simplify the system boundary of building materials that encompasses material extraction, manufacturing and transportation processes, shown in Fig. 1 with boundary of solid line. And then we expend the boundary system to the phase of material recovery and energy recovery, shown with dotted line. In the following analysis, we assume that after building's demolition, material recovery includes wasted aggregate and steel, which can be recycled through proper process for the future use. Energy recovery indicates that demolished wood is burned as bio-energy source to substitute fossil fuel to produce energy instead of land filling.

This paper assumes 80% of material and energy recovery in the analysis. 80% of the waste concrete can become crushed aggregate and the remaining 20% of the concrete is lost during recovery and recycling process. For instance, it cannot practically possible to recover all the concrete in foundations and some of the concrete will break down into small particles and be absorbed into the soil. As for demolished wood, it is also assumed that 80% of wood can be recovered for energy source, with remaining either to be land filled or to be left at the demolition site because all demolition wood cannot be collected for the technical reasons. Besides, wood is degraded and damaged by fungus or insects, or humid climate in Taiwan. Finally, it is assumed 80% of waste steel can be recycled for substituting for steel ore in manufacturing reinforcing bar, because some portion of steel in regions of dense steel reinforcement in joint cannot be easily cut and recycled, or is lost during recovery process. In the following analysis, it is assumed that the densities of concrete, steel and wood are 2.400 kg/m3, 7,750 kg/m3 and 550 kg/m3 respectively.

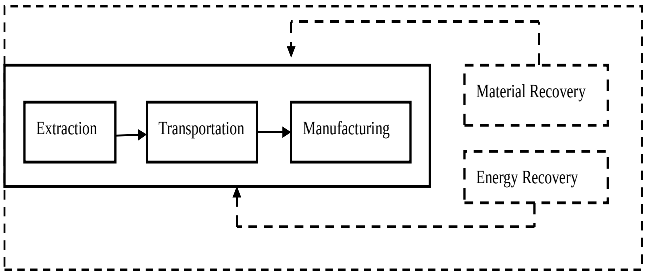

Figure 1. System boundary.

B. Environmental Impacts of Construction Materials

Concrete, steel and wood are the major materials for reinforced concrete structure, steel structure and wood structure. Concrete is widely used in building construction in Taiwan and most of the buildings are RC structure. The primary energy consumed for concrete is cement production, during which mineral raw materials are heated in a kiln to produce clinker. Fuel combustion for kiln firing is the largest source of energy consumption and CO2 emissions in production. It has been estimated that each tonne of cement produces 409.57 kg CO2 and consumes energy of 3,984MJ [17]. In addition, stone aggregate in the form of sand and gravel is an important component of concrete, composing more than 80% by weight of a typical concrete composition. Stone aggregate is extracted near the river bank in Taiwan and it is estimated that each cubic meter of aggregate during extraction releases 3.11 kg CO2 and consumes energy of 33.9MJ [17]. Thus, to make precast concrete, a concrete mixer machine is used in the process with estimation of 1.34 kg CO2 emissions and 7.3 MJ energy requirements per cubic meter of concrete [17].

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Besides, as for steel material, the source of steel ore is imported from the West of Australia and is remanufactured into steel products through blasting and casting in Taiwan. The first process ore mining indicates extracting rock or minerals from the earth by their removal from an open pit. Energy consumption for various operations includes drilling, dosing and extraction. Based on literature, energy consumption per tonne ore requires about 1,280 [18] and it is taken each unit of mega joule of oil releases 0.07 kg CO2 in the calculation, leading to CO2 emissions of 89.6 kg per tonne of ore mining.

After ore mining, mineral processing aims at making the ore suitable for subsequent process and uses. Comminution is the particle size reduction of materials and it is the major consumer of energy in mineral processing and general mineral processing plant use electric power for conveying or pumping the ore through a sequence of treatment, which includes crushing, floating and filtration. It has been estimated that energy consumption in comminution needs 30 kWh/tonne ore (108 MJ/tonne ore) [19]. After mineral processing, iron ore is transported to the coast by rail for marine transportation to Taiwan. It is estimated that the distance from the location of mineral processing in the west of Australia to port Hedland takes around 300 km; the distance by marine transportation from Hedland to Kaohsiung takes 4,873 km. Bulk cargo ship is used in the following analysis. Environmental impacts of rail and marine transportation are estimated by the author with the methodology provided by NTM (Network for Transport & Environment) [20, 21]. Factors and information of rail and marine transportation are shown in Table 1 and 2.

After the processed ore is imported to Taiwan, there comes the process of making steel products, such as reinforcing bar, section steel and so on. It is estimated that steel manufacturing process requires greater energy consumption (7,857 MJ/tonne) and releases higher CO2 emissions (964 kg/tonne) [17].

Due to insufficient forest resources and forest protection policy in Taiwan, a great amount of wood is imported from North America. Besides, in order to protect forest resources in Taiwan, government has made laws to forbid most of wood in forest in Taiwan. Thus a great amount of wood is imported from overseas to Taiwan. Since forest resources in North America including USA and Canada are abundant and the wood price is reasonable for market, North America becomes one essential wood importation source for Taiwan.

It is assumed that wood from Canada (British Columbia Province, West Canada) is imported to Taiwan for use. Environmental impacts of wood through processes of harvesting, road transportation from forest to sawmill and manufacturing are available from Canada Athena Institute Reports (Athena Sustainable Materials Institute) [22]. Besides, it is estimated that the major locations of sawmills in this province are Vanderhoof, Quesnel, Brackendale and Hagensborg. The average distance from sawmills to the marine port Vancouver takes 409 km. It is assumed that Heavy Duty Vehicle (HDV) (40 tonne) is used in road transportation, with assumption that only 75% of carrying capacity for wood is used [23]. Factors of information of road transportation by truck are shown in Table 3.Beides, long journey of marine transportation is another factor for environmental impacts. Container cargo ship is used in the estimation. The distance from Vancouver to port Kaohsiung takes 10,376 km and the calculating methodology is also provided by NTM. The factors and information of marine transportation is shown in Table 4.

TABLE I. FACTORS AND INFORMATION OF RAIL TRANSPORTATION

	Diesel Train
Train Gross Weight, W(gr) (tonne)	1,000
CO_2 Emission Factor (g/kg)	3,175
Load Factor (%)	60
Fuel Heating Value (MJ/kg)	42
Fuel Consumption (g/gr-tkm)	$122*W(gr)^{-0.5}$

TABLE II. FACTORS AND INFORMATION OF BULK CARGO MARINE TRANSPORTATION

	Bulk Cargo Ship
Cargo Capacity (tonne)	50,000
Carrying Capacity (%)	67
Fuel Consumption (tonne/km)	0.047
CO_2 Emission Factor (kg/tonne fuel)	3,179
Fuel Heating Value (MJ/kg)	41

TABLE III. FACTORS AND INFORMATION OF ROAD TRANSPORTATION BY TRUCK

	Heavy Duty Vehicle
CO_2 Emission Factor (kg/litre)	2.67
Carrying Volume (m^3)	27.3
Carrying Capacity (%)	75
Fuel Heating Value (MJ/litre)	38.65
Fuel Efficiency (litre/100km)	30.89

TABLE IV. FACTORS AND INFORMATION OF CONTAINER CARGO SHIP MARINE TRANSPORTATION

	Container Cargo Ship
Cargo Capacity (TEU)	6,000
Carrying Capacity (%)	80
Cargo Volume (m^3)	25
Fuel Consumption (tonne/km)	0.163
CO_2 Emission Factor (kg/tonne fuel)	3,179
Fuel Heating Value (MJ/kg)	41

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C. Construction and Deconstruction Phase

Building construction includes burdens from electricity used for power tools, as well as fossil fuel used by heavy equipment at the construction site. Construction activities include site preparation, envelop installation, mechanical equipment installation and so on. It has been estimated that contribution of the on-site construction phase of energy needs account for 5% to 12% of the total energy used to produce building materials [24]. And it has been discovered that construction energy is equal to 7% of material manufacturing process [25]. In Sweden, Adalberth [26] investigated houses, finding that building construction consumes energy of 74 kWh/m2. In Taiwan it has been estimated that energy required for construction consumes only 18.10kWh/m2 [17], much lower than energy consumption during manufacturing process.

On the other hand, as for demolition phase, only small amount of energy consumption is used in demolition process. It has been investigated that energy use might be less than 3% of the energy content of the demolition waste [26]. In Taiwan, excavator is used in the demolition process and it is estimated than 29.4MJ/m2 of energy is needed, with CO2 emissions of 2.16 kg/m2 [17]. Therefore, either in construction or in demolition phase, environmental impacts reveal relatively small. Thus, in this research the environmental burdens during construction and deconstruction phases will not be considered due to small amount of energy consumption during mechanical operation.

D. The Estimative Usage Amount of Building Materials and Functional Unit

In order to assess the environmental impacts of building structures, the amount of materials used would be required in Taiwan [12, 27]. The outcome is shown in Table 1. In the following, only the major materials in three structures are analysed and materials for inner decoration are not taken into account. In addition, a frequently adopted functional unit is the unitary-usable floor area, sometimes with the whole life span and sometimes with reference to per year. Nevertheless, in the following analysis, floor area (m2) is adopted for estimation. It can be found that in Taiwan, steel is the major construction material in steel structure 179.8 kg/m2, more than RC structure and wood structure. As for the usage of concrete, the consumption of it for RC structure amounts to the highest 0.624 m3/m2, while for wood and steel structure, concrete consumption differs not much.

TABLE V. ESTIMATIVE USAGE OF BUILDING MATERIALS IN STRUCTURES IN TAIWAN

	RC Structure	Wood Structure	Steel Structure
Steel (kg/m^2)	159.81	22.4	179.8
Concrete (m^3/m^2)	0.624	0.17	0.18
Wood (m^3/m^2)	--	0.15	--
Plywood (m^3/m^2)	--	0.046	--

E. Environmental Impacts of Recovery Process

Typically, demolished concrete can be crushed into recycled aggregate. However, it has been discovered [28] that the physical properties of recycled aggregate have the difference in water absorption from 3% to 12% for coarse and fine fractions. This value is much higher than that of the natural aggregates whose absorption is about 0.5% to 1%, thus leading to the problem of workability and the slum loss, which means the loss of consistency in fresh concrete with time. Additionally, another important property of recycled concrete is the compression strength. It has been investigated that there is a reduction in strength in recycled aggregate, but it should be noted that the extent of reduction is related to parameters such as the type of concrete used for making recycled aggregate (high, medium or low strength), replacement ratio, water/cement ratio and moisture content of the recycled aggregate [29]. Although recycled aggregate is being under discussion for its physical property, a higher quality control is therefore needed in the production and the use of crushed concrete as aggregate in new concrete.

After demolition, the disassembled concrete material is first crushed with jaw crusher machine until the pieces are small enough for further processing. Hammer crusher machine is used for the second process to sort the recycled aggregate by size. It has been investigated that energy requires 6 MJ and 77.14 MJ for jaw crusher and hammer crusher for processing per tonne of recycled aggregate [30]. It is assumed that the major fuel used in processing is fuel oil, which produces 0.073 kg CO2 per MJ. Therefore, each tonne of recycled aggregate consumes 83.14 MJ and releases 6.06 kg CO2. Based on the literature, energy demand for production of crushed aggregate is about three times higher than for extracting natural aggregate [31].

The iron cycle, in which recycling is well established, is a mature process, with a history dating back thousands of years even though extensive production of steel did not begin until the 19th century. The steel industry has a well-established infrastructure for scrap collection because this scrap is a feedstock to the steel manufacturing process, which uses between 20% and 100%, recycled steel to manufacture new steel. Based on the Steel Recycling Institute [32], around 70Mt are recycled steel in the North America. Each tonne of recycled steel saves 1,100 kg of iron ore, 600 kg of coal and 50 kg of limestone. It has been discovered that from the American Institute of Architects environment Resource Guide [33], each kilogram of steel produced from recycled sources instead of from raw material extraction reduces 12.5MJ of energy. In addition, 47% less oil is consumed, 86% less water is used and 97% less mining waste is created. Thus, there are great benefits of recycling waste steel.

The process of recycling steel is called electric arc furnace. Steel scrap is first tipped into the electric arc furnace from an overhead crane. A lid is then swung into position over electric arc furnace. An electric current is passed through the electrodes to form arc. The heat generated by this arc melts the scrap. During the melting process, other metals are added to the steel to give it the required chemical composition. Also oxygen is blown in to the electric arc furnace to purify the steel. It has been investigated in Taiwan that each tonne of

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recycled steel requires energy 4,107.8 MJ, releasing 578.36 kg CO2 during the process [17].

At the end of service life of wood in building, it can be reused or recycled for additional material use; however, there exist problems of technical and economical constrains. Most of the waste wood is either burned or land filled in Taiwan. Land filling demolished wood is prohibited in many parts of the European Union. For example, as sorted combustible material, demolition wood is not permitted to be deposited in landfills in Sweden. Wood is the most common biomass that can be used as bio-fuel to produce energy. The energy source that recovered bio-fuels replace influences the outcome of a life cycle assessment [34]. Worldwide, it has been investigated that global primary energy use includes 26% for coal, 34% for oil and 21% for fossil gas in 2006 [35]. In Taiwan, fossil fuel consumption accounts for 91.3% of total energy source in 2010 and the government has legislated for renewable policy up to 8% by 2025 [36]. Besides, IPCC scenario analyses suggest that fossil fuels are still very likely to account for share of the global primary energy use in the year 2100 [37].Therefore, to reduce the global warming, a bio-fuel should be used to replace fossil fuels.

In the following analysis, it is assumed that waste wood is recycled and used as energy source to substitute natural gas in manufacturing process. It is assumed that the amount of thermal energy provided by waste wood substitutes the same amount of thermal energy provided by fossil fuels. The energy content in wood is assumed to be 15.8 KJ/kg, which gives a CO2 emission of 32 g C/MJ. Each cubic meter of natural gas produces energy of 37.2 MJ and releases CO2 of 2.08 kg. Therefore, thermal energy produced by wood (21.56 kg) is equivalent to that produced by natural gas (9.16 m3), leading to 20.91 kg CO2 that can be substituted by wood. CO2 emissions of wood burning are regarded negative due to the intake of CO_2 in the air during the growth of wood.

F. Displacement Factor (DF)

A displacement factor (DF) for wood structure substitution is a measure of the amount of energy consumption (EC) and greenhouse gas (GHG) emissions and which can be avoided when wood structure is applied in building construction instead of steel structure and RC structure. A higher displacement refers that more greenhouse gas emissions are reduced and more energy consumption is avoided. In addition, CO2 emissions as greenhouse emissions are taken in the analysis. The displacement factor (DF) can be expressed in the following. In the equation (1) to (2), RCS indicates reinforced concrete structure; SS indicates steel structure; and WS indicates wood structure.

$$DF_{EC\,(RCS\text{-}WS)} = (EC_{RCS} - EC_{WS}) / EC_{WS} \quad (1)$$

$$DF_{EC\,(SS\text{-}WS)} = (EC_{SS} - EC_{WS}) / EC_{WS} \quad (2)$$

Equation (1) indicates factor of energy consumption saved by wood structure in replacement of RC structure; equation (2) indicates factor of energy consumption saved by wood structure in replacement of steel structure.

$$DF_{GHG\,(RCS\text{-}WS)} = (GHG_{RCS} - GHG_{WS}) / GHG_{WS} \quad (3)$$

$$DF_{GHG\,(SS\text{-}WS)} = (GHG_{SS} - GHG_{WS}) / GHG_{WS} \quad (4)$$

Equation (3) indicates factor of greenhouse gas avoided by wood structure in replacement of RC structure; equation (4) indicates factor of greenhouse gas avoided by wood structure in replacement of steel structure.

III. RESULTS AND DISCUSSION

Firstly, when the construction phase of materials of three structures is considered, it can be found in Fig. 2 that RC structure requires the highest amount of energy (2,600 MJ), more than steel structure (2,100 MJ) and wood structure (1,100 MJ). Wood structure has therefore the lowest embodied energy requirements. Embodied energy needs of steel material accounts for 62% and 85% of total consumption for RC structure and steel structure, respectively, due to high energy consumption in steel manufacturing. Besides, displacement factors DFEC (RCS-WS), DFEC (SS-WS) for construction phase in terms of energy consumption are 1.36 and 0.88. This indicates that RC structure has a higher substitution effect on energy reduction than steel structure.

On the other hand, in terms of embodied CO2 in Fig. 3, wood structure with forest resource from Canada has the greatest benefit to reduce global warming. The amount of CO2 emissions of RC and steel structure is 3.1 and 2.2 times more than wood structure. It can be calculated that, displacement factors, DFGHG (RCS-WS) and DFGHG (SS-WS) equal to 2.1 and 1.2.

Secondly, when the strategy of material and energy recovery (80%) is considered, the results have shown in Fig. 2 that steel has greater embodied energy offset in RC structure and steel structure. For RC structure, 20% (525 MJ) of energy can be offset by material recovery, while for steel structure, 28% (590 MJ) of energy consumption can be offset. Recycled steel does not contribute much in energy savings for wood structure due to small amounts. In addition, waste wood used as bio-fuel produces a great amount of energy of 1,362.6 MJ, which offsets energy more than total consumption in wood construction, leading to negative value in life cycle balance. Recycled aggregates do not contribute to high energy offset in three structures, accounting for 3.8% (99.6 MJ), 2.4% (27.1 MJ) and 1.3% (28.6 MJ) for RC, wood and steel structures respectively simply because the process of recycling aggregate through mechanical operation accounts for small amount of emissions. The life cycle energy balances for RC structure, wood structure and steel structure are 1,984 MJ, -362 MJ and 1,460 MJ respectively. If the wood structure is used to substitute for RC and steel structures, displacement factors, DFEC (RCS-WS) and DFEC (SS-WS) would show 6.5 and 5.0.

Additionally, in another aspect of life cycle CO2 emissions balance in Fig. 3, recycled steel in RC structure can offset 22.2% (74 kg) of CO2 emissions of the total amount, and can again offset 35% (83.2 kg) in steel structure, while only 10% (10.4 kg) of CO2 emissions are avoided in wood structure. When waste wood is burned as bio-energy to substitute natural gas, -83.6 kg of CO2 emissions are avoided in wood structure. Besides, recycled aggregates, likewise, do not contribute to great amount of avoided CO2 emissions It

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can be found that life cycle CO2 balances for RC, wood and steel structures show 251.5 kg, 12.83 kg and 155.83 kg respectively. Wood structure shows almost 'zero embodied CO2 emissions' of materials. The displacement factors of DFGHG (RCS-WS) and DFGHG (SS-WS) are 18.6 and 11.1, revealing that RC structure has a very high substitution effect on CO2 emissions.

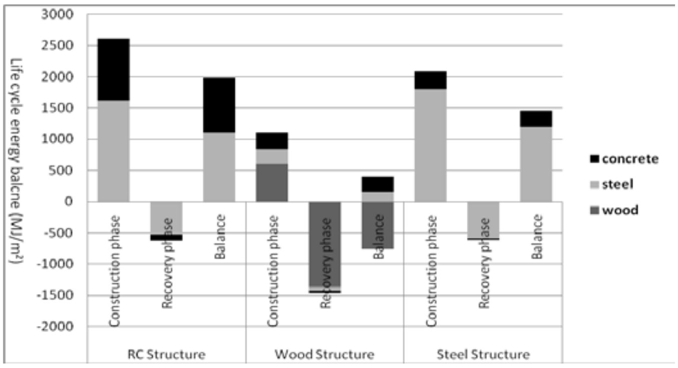

Figure 2. Life cycle energy balance of structures.

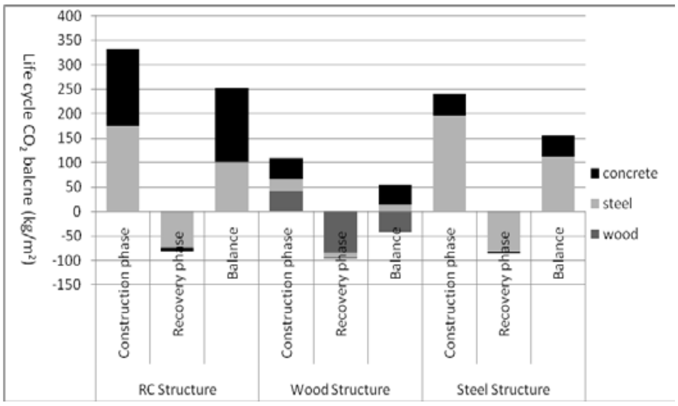

Figure 3. Life cycle CO_2 balance of structures.

IV. CONCLUSION

In the above analysis, firstly, considering the life cycle balance, wood structure has great benefits for the built environment in Taiwan even though the wood is transported far from Canada. RC structure has high environmental impacts such as energy consumption and CO_2 emissions.

Secondly, it can be seen that recycled aggregates do not offset much of the environmental impacts in terms of embodied energy and CO_2 emissions compared with wood and steel; however, this does not mean material recovery of recycled aggregate is not essential because some aggregates are illegally extracted near some river bank, which is forbidden to extract in Taiwan, thus leading to the destruction of local ecology and having the danger of landslides. In consequence, recycled aggregates can avoid more natural aggregates are illegally extracted.

Thirdly, as for displacement factors, if we consider the strategy of material recovery, factors increase much more than the construction phase, thus indicating that post-use recovery phase is also essential, especially in CO_2 emissions. Instead of land filling, recycling the waste of wood to be used as bio-energy to substitute for fossil fuels can significantly reduce environmental impacts.

Fourthly, in this paper we assume 80% of materials are recovered, and it seems too ideal and in reality, this may not occur. After many years of life of a building, 50 years, taken for an example, the great uncertainty still remains. The purpose of this paper is not only to foresee the future perspective but also to investigate how much embodied energy can be avoided and how much CO_2 emissions can be reduced if recovery strategy of materials is completed at present. Therefore, the main goal is to enhance recycling of building materials and at the same time to develop more recovery strategies which can mitigate environmental burdens effectively.

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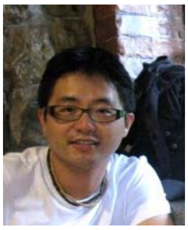

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