Research on the optimal scheme of 3E game for lightweight body-in-white under environmental protection policy

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Abstract
Lightweight of body-in-white (BIW) can effectively achieve energy saving and emission reduction, is an important component of automobile lightweight, and how to ensure better economy while lightweight has attracted wide attention from industry and academia. This study deeply analyzed the stages of the full life cycle of internal combustion engine vehicle (ICEV) and battery electric vehicle (BEV), deconstructs the stages where the weight of BIW has a greater impact on the two, and introduces the concept of full-cycle closed-loop flow of materials to establish universal “Energy-Environment-Economy” Evaluation Model, also called 3E assessment model for auto components. In addition, the 3E-PSI model is established in combination with the PSI method, which further makes up for the shortcomings of the general 3E model that cannot select the optimal solution by considering energy consumption, emissions, and economy comprehensively. The 3E-PSI analysis of material lightweight of BIW is conducted, which takes the ICEV and BEV on the same platform as an example. The results show that in terms of energy consumption, the magnesium alloy BIW of the ICEV is the lowest, however, the aluminum alloy BIW of the BEV is the lowest. In terms of environmental emissions, magnesium alloy BIW is the lowest in both ICEV and BEV, which are 57% and 59.56% of ordinary mild steel BIW respectively; As far as economy is concerned, the ICEV have break-even points for all lightweight materials in the total mileage during lifetime, and the BEV only has a break-even point, that is, driving 78625.68 km, the cost of high-strength steel BIW is lower than ordinary low-carbon steel. In addition, the comprehensive optimal scheme of ICEV is BIW of magnesium alloy material, and the comprehensive optimal scheme of BEV is BIW of aluminum alloy material.

Keywords
Lightweight of BIW, internal combustion engine vehicle, battery electric vehicle, preference index selection method, “Energy-Environment-Economy-PSI” model

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Introduction
Automobile products have the characteristics of high technical complexity, high energy consumption, high emissions and high cost. In the face of the increasing non-tariff barriers built by China after entering the WTO, especially the “green barriers” and the increasingly stringent national green development policies and standards, energy saving and emission reduction have become an urgent need for automotive products to stand. Coupled with the full outbreak of natural
disasters around the world in early 2020, the protection of
the environment will surely bear a profound brand
on the minds of automobile consumers. There are three
main ways for energy saving and emission reduction of
automobile products. One is to develop new energy
vehicles, especially battery electric vehicles; the second
is to develop efficient engine technology; the third is to
apply lightweight technology. At present, new energy
vehicles are in the initial stage, the bottleneck of battery
technology and the shortage of charging facilities still
need to be solved. According to statistics, the number of
new energy vehicles in 2019 is only 3.81 million, and
there is still a long way to go for efficient engine tech-
ology to break through the bottleneck of 38%. Therefore,
lightweight technology has become an important way of
energy conservation and emission reduction.

Countries around the world have carried out differ-
ent research projects on vehicle lightweight, such as
new generation automotive partnership (PNGV) in the
United States, ultra-light vehicle program (SLC) in the
European Union and ultra-light steel body project
(ULSAB) in the international iron and Steel
Association. International Iron and Steel Institute
research shows that the weight of steel body structure
may be reduced by more than 35% compared with the
current benchmark internal combustion engine vehicle
in the future, and the emission may be reduced by
nearly 70% in the whole life cycle. With the application
of aluminum alloy, magnesium alloy, high strength
steel and advanced composite materials, scholars at
home and abroad have also carried out life cycle assess-
ment (LCA) and life cycle cost (LCC) research on vehi-
cle material lightweight, among which LCA research is
more, and mainly focused on parts, such as BIW, hood,
seats, hub/rim, auxiliary instrument panel, intake
manifold, etc., and the research on the whole vehicle has also appeared. Some scholars have also studied the life cycle cost after lightweight, Akshti et al. have compared the LCC of the glass fiber reinforced material engine hood and the hybrid fiber reinforced material engine hood. Xu and Yang have further optimized the energy consumption, emission, and cost of BEV and ICEV.

As mentioned before, domestic and foreign scholars
have conducted in-depth LCA research on automobile
parts, and most of them are related to the lightweight
of automobile parts. In recent years, the LCA research
of the whole vehicle is becoming more and more
mature. Considering the practical engineering applica-
tion, LCC research on automobile parts and vehicle is
also gradually carried out. The material lightweight
technology of BIW is not mature, and it still has great
potential. However, it is also a complex system engi-
eering, which not only needs to achieve the
optimization of energy consumption, emission, and
economy, but also takes full account of the difference
between ICEV and BEV. Different from the current
research, a universal 3E-PSI evaluation model is estab-
lished based on the lightweight characteristics of BIW,
and its effectiveness is verified by taking ICEV and
BEV on the same platform as research carriers. The
model considers energy consumption, emission and
economy at the same time, and introduces the closed-
loop flow concept of material life cycle, which greatly
reduces the evaluation loss of materials. Different from
other 3E studies, this study uses the emerging PSI
method to determine the optimal scheme of BIW mate-
rinal in the context of “Energy-Environment-Economy”
game. This research has carried out a systematic and
in-depth study on the lightweight of BIW material,
which can provide methodological reference for the
lightweight research of other parts. The research results
provide decision-making support for the government
to formulate environmental protection policies in the
automotive field, provide theoretical guidance for the
exploration of the industry’s energy-saving emission
reduction path, and provide a scheme reference for the
enterprise’s lightweight route.

Methodology

Usually, the material flows are systematically deter-
mined in upstream chains, production phase, use phase,
and at the end-of-life of a product (Life Cycle
Inventory, LCI). Then, critical emissions into the dif-
ferent environmental compartments (water, air, soil)
are allocated to environmental impact categories (Life
Cycle Impact Assessment, LCIA) in order to better
estimate the overall environmental impact potential.
The methods apply LCI indicators when only the mate-
rial and energy flows are to be quantified. LCIA indica-
tors are used either at the midpoint level when the
focus is set on the interpretation of LCA results
with respect to different environmental impacts, for
example, Global Warming Potential, Acidification
Potential, Eutrophication Potential, or Ecotoxicity
Potential, or at the endpoint level when damages,
for example, to Human Health, Natural Resources,
Natural Environment, or Biodiversity, are in the fore-
ground (EN ISO 14040, 2009; EN ISO 14044, 2006).
With endpoint methods such as Eco-Indicator 99, envi-
ronmental damages may also be aggregated into a sin-
gle score facilitating the cross-dimensional comparison
of alternative products. This study follows the LCA
technique standardized by ISO 14040 and 14044
instructions which includes four steps: goal and scope
definition, inventory analysis, impact assessment, and
interpretation, as show in Figure 1.
This study discusses the influence of BIW material lightweight on energy, environment and economy. Therefore, the influence of these three attributes should be comprehensively balanced when selecting materials suitable for the BIW of ICEV and BEV. PSI (Preference Selection Index) Method is a new multi-attribute decision-making method which does not need to consider the complex weight relations among multiple attributes. When the relative weight relationship between the design attributes conflicts or is difficult to determine, the advantages of PSI without determining the weight are reflected, which makes the PSI method more suitable for the decision-making process of considering multiple selection criteria and alternative objects at the same time. In this study, the weight relationship between energy attribute, environmental attribute, and economic attribute is difficult to determine. Therefore, the PSI method is selected to determine the optimal BIW scheme for ICEV and BEV.

In the PSI method, it is necessary to calculate the final preference index of each alternative material. The alternative material with the highest final preference index is considered as the best choice. The steps of PSI method are shown in Figure 2.

**Goal and scope**

The goal of this study is to compare the influence of BIW material lightweight on “Energy-Environment-Economy,” and then choose the best BIW material to assist the government to make energy saving and emission reduction policies, which can also provide theoretical reference for the selection of BIW lightweight materials in automobile enterprises. BIW, as an important part of automobile, is a common component of ICEV and BEV. At present, under the impact of policies, mainstream vehicle enterprises have laid out BEVs, forming a situation of common development of ICEVs and BEVs. There are four kinds of materials for BIW: low-carbon steel, high-strength steel, aluminum alloy and magnesium alloy, which will be applied to ICEV and BEV, respectively.

**Functional unit.** The functional unit is defined as the quantified performance of a product system for use as a reference unit. The functional unit of this study is that the BIW with four different materials is applied to the ICEV and BEV on the same platform respectively, and both the ICEV and BEV drive 150,000 km under the road conditions in China. The energy, environment and economic performance of BIW used in ICEV and BEV are significantly influenced by the whole life cycle mileage and road conditions. This functional unit allows capturing the influence of these key parameters. Furthermore, it also enables the study to compare with other research on lightweight of BIW materials.

**System boundary.** Figure 3 shows the system boundary of energy consumption, emission and cost in the whole life cycle of BEV and ICEV in the context of BIW material lightweight. It can be seen from the analysis that raw material acquisition stage, manufacturing and assembly stage, use stage, and scrap recovery stage are the main influence stages of BIW material lightweight, and the small difference in transportation stage can be ignored. The materials needed for material manufacturing in the raw material acquisition stage come from the
raw materials produced by mining of mineral resources and the recycled materials in the waste. The materials in the waste include not only the metal waste produced by the scrap of BIW, but also the leftover materials produced in the material processing stage.

Underlying assumptions.

1. The lightweight of BIW only considers the replacement of light-weight materials, not the change of manufacturing process, structure,
The calculation model of "Energy-Environment-Economy-PSI" (3E-PSI)

In this paper, the influence of BIW material lightweight on ICEV and BEV in the full life cycle is studied. Therefore, the calculation model should be fully explored around the change of BIW materials and quality. Through combing the key stages of its life cycle, this paper establishes a universal evaluation model, as shown below.

For the calculation of energy consumption of traditional vehicles and new energy vehicles, as shown in formula (1)–(2):

\[ E_C = \sum_{i} \sum_{j} E_{CBIW_i} \]

\[ E_{CBIW_{ij}} = \sum_{k} M_{BIW_k} \bullet \sum_{i=1,2} \sum_{j} E_{C_{d_{i,j}}} + \sum_{k} M_{BIW_k} \bullet \eta_r \bullet \sum_{j} \sum_{i=3} \sum_{j} E_{C_{d_{i,j}}} + \left[ \sum_{k} M_{BIW_k} \bullet \eta_i \bullet \sum_{j} \sum_{k=4} \sum_{j} E_{C_{d_{i,j}}} - \sum_{k} M_{BIW_k} \bullet \eta_p \bullet \sum_{i=1} \sum_{j} E_{C_{d_{i,j}}} - \sum_{k} M_{BIW_k} \bullet (1-\eta_r) \bullet \sum_{i=1} \sum_{j} E_{C_{d_{i,j}}} \right] \tag{2} \]

where \( E_C \) represents the total energy consumption of the BIW on the ICEV or BEV during the full life cycle. \( E_{CBIW_i} \) refers to the consumption of the \( j \)-th energy in phase \( i \) of the BIW on ICEV or BEV, where \( i = 1, 2, 3, \) and \( 4 \), respectively, indicating raw material acquisition stage, manufacturing and assembly stage, use stage, and scrap recovery stage. \( M_{BIW_k} \), \( k \), and \( \eta_r \) represents the quality of material \( k \). Material type and the recycling rate of BIW respectively. \( E_{C_{d_{i,j}}} \) represents the consumption of the \( j \)-th energy in the \( i \)-stage of the ICEV or BEV. \( \eta_i \) indicates the material utilization rate of BIW in the material processing stage.

For the calculation of emissions of BIW in ICEV and BEV, as shown in formula (3)–(7):

\[ E_P = \sum_{i} \sum_{j} E_{PB\text{IW}_i} \]

\[ E_{PB\text{IW}_{ij}} = \sum_{k} M_{BIW_k} \bullet \sum_{i=1,2} \sum_{j} (E_{P_{d_{i,j}}} + E_{P_{d_{i,j}}}) + \sum_{k} M_{BIW_k} \bullet \eta_i \bullet \sum_{j} \sum_{i=3} \sum_{j} (E_{P_{d_{i,j}}} + E_{P_{d_{i,j}}}) + \left[ \sum_{k} M_{BIW_k} \bullet \eta_i \bullet \sum_{j} \sum_{k=4} \sum_{j} (E_{P_{d_{i,j}}} + E_{P_{d_{i,j}}}) - \sum_{k} M_{BIW_k} \bullet \eta_p \bullet \sum_{i=1} \sum_{j} \sum_{k} (E_{P_{d_{i,j}}} + E_{P_{d_{i,j}}}) - \sum_{k} M_{BIW_k} \bullet (1-\eta_r) \bullet \sum_{i=1} \sum_{j} \sum_{k} (E_{P_{d_{i,j}}} + E_{P_{d_{i,j}}}) \right] \tag{4} \]

\[ E_{PB\text{IW}_j} = \{(E_{PB\text{IW}_j})_{GWP},(E_{PB\text{IW}_j})_{AP},(E_{PB\text{IW}_j})_{EP},(E_{PB\text{IW}_j})_{POCP}, \ldots,(E_{PB\text{IW}_j})_{\phi}\} \tag{5} \]

\[ (E_{PB\text{IW}_j})_{\phi} = \sum_{j} \sum_{i} E_{PB\text{IW}_ij} \times T_{\phi} \tag{6} \]

\[ E = \frac{(E_{PB\text{IW}_j})_{\phi} \times W_{\phi}}{R_{\phi}} \tag{7} \]

where \( E_P \) refers to the total pollutant emission of the BIW in ICEV or BEV during the full life cycle. \( E_{PB\text{IW}_{ij}} \) denotes the emission of the \( j \)-th pollutant in the \( i \)-th stage of BIW with \( k \)-th material in the ICEV or BEV. \( E_{P_{d_{i,j}}} \) denotes the direct emission of the \( j \)-th pollutant in the \( i \)-th phase of BIW with \( k \)-th material in ICEV or BEV. \( E_{P_{d_{i,j}}} \) denotes the upstream emission of the \( j \)-th pollutant in phase \( i \) of BIW with \( k \)-th material in ICEV or BEV. \( (E_{PB\text{IW}_j})_{\phi} \) denotes the amount of all pollutants that have an effect on the \( \phi \)-th type of environmental impact. \( T_{\phi}, R_{\phi}, \) and \( W_{\phi} \) represent the characteristic factor, standardized reference value and weights of the \( \phi \)-th type of environmental impact, respectively. \( E \) denotes the comprehensive environmental impact value of lightweight BIW materials for ICEV or BEV.

For the calculation of economy of BIW in ICEV and BEV, as shown in formula (8)–(9):

\[ E_M = \sum_{k} \sum_{i} E_{MB\text{IW}_{ia}} \tag{8} \]

\[ E_{MB\text{IW}_{ia}} = \left[ \sum_{k} M_{BIW_k} \bullet \sum_{i=1,2} \sum_{j} E_{M_{a,i}} + \sum_{k} M_{BIW_k} \bullet \eta_p \bullet \sum_{j} E_{M_{a,i}} + \left[ \sum_{k} M_{BIW_k} \bullet \eta_i \bullet \sum_{j} \sum_{k=4} \sum_{j} E_{M_{a,i}} - \sum_{k} M_{BIW_k} \bullet \eta_p \bullet \sum_{i=1} \sum_{j} \sum_{k} E_{M_{a,i}} - \sum_{k} M_{BIW_k} \bullet (1-\eta_r) \bullet \sum_{i=1} \sum_{j} \sum_{k} E_{M_{a,i}} \right] \right] + E_{M_{p}} \tag{9} \]
where $E_M$ represents the total life cycle cost of BIW in the ICEV or BEV. $E_{MBW}$ denotes the cost of BIW with the $k$-th material in phase $i$ for ICEV or BEV. $E_{MI}$ denote the cost in the $i$-th stage of BIW with the $k$-th material in the ICEV or BEV. $E_{MP}$ represents the power system cost of ICEV or BEV.

For the selection of optimal material of BIW in ICEV and BEV, as shown in formula (10)–(13):

$$X_{ij} = \frac{\sum_i \sum_j x_{ij}}{x_{ij}}$$

$$W_{ij} = \frac{x_{ij}}{x_{ij}}$$

$$PV_j = \sum_{i=1}^{N} [W_{ij} - \bar{W}_j]^2$$

$$\psi_j = \frac{1 - PV_j}{\sum_{j=1}^{M} (1 - PV_j)}$$

where $X_{ij}$ represents decision matrix; $x_{ij}$ represents each property value ($i = 1,2,3$), ($j = 1,2,3,4$); $W_{ij}$ represents the standardized value of each property of the candidate material; $x_{ij}^\text{min}$ represents the minimum value of a certain property; $PV_j$ represents the preference change value, and $W_j$ represents the average value of each alternative in the evaluation standard after standardization. In the formula, $\psi_j$ represents the overall preference index.

**Inventory analysis**

The data used in the Life Cycle Inventory (LCI) come from relevant studies of other scholars and reports as well as industrial partners’ information and are documented in this section. GaBi database is used as the source of background LCI data.

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### Table 1. The main parameters of BIW for ICEV and BEV.

| The type of vehicle | BIW | Engine | Transmission | Driving motor | Power battery | Motor controller | Curb weight |
|---------------------|-----|--------|--------------|---------------|---------------|------------------|-------------|
| ICEV                | 363 | 129    | 34           | 0             | 0             | 0                | 1349        |
| BEV                 | 390 | 0      | 20           | 41            | 300           | 14               | 1480        |

### Table 2. Influence of lightweight materials on BIW and vehicle.

| Materials          | Mass of BIW kg | Mass of ICEV kg | Mass of BEV kg | Cost of material ¥/t |
|--------------------|----------------|-----------------|----------------|----------------------|
| Low-carbon steel   | 272            | 1349            | 1480           | 3.5                  |
| High-strength steel| 242            | 1319            | 1450           | 5.0                  |
| Aluminum alloy     | 136            | 840             | 917            | 11.0                 |
| Magnesium alloy    | 101            | 811             | 885            | 27.0                 |

The outline dimensions of the examples in this study are $4295 \text{ mm} \times 1705 \text{ mm} \times 1555 \text{ mm}$. The fuel consumption of the ICEV is 8L in 100 km, and that of the BEV is 14 kwh. In order to highlight the research objectives, only the parameters of the power system which are the main differences between the ICEV and the BEV are shown. The main parameters of BIW for ICEV and BEV are shown in Table 1.

In this paper, the power battery is ternary lithium battery, with energy density of 150wh/kg, power density of 700 W/kg, 15 cycle life of 1500 times (to 80% of the remaining capacity), and unit capacity price of 2725 yuan. The driving motor is a permanent magnet synchronous motor widely used in BEV, with a peak power of 98.01 kw, a power density of 2.4 kw/kg, and an average motor cost of 80 yuan/kW.

**Raw material acquisition stage.** The automobile consists of four parts: engine, chassis, body (BIW, interior, and exterior decoration) and electric control system. Since lightweight materials are mostly used in the manufacture of BIW (body frames and covers), the light-weight object in this study is BIW, but does not include covers. The three selected lightweight materials are: high strength steel, aluminum alloy, and magnesium alloy. The BIW mass and vehicle mass after the application of lightweight materials are shown in Table 2.

BIW will inevitably cause material loss in stamping process. The study found that the main schemes for improving the utilization rate of body-in-white stamping parts are: styling optimization, structure optimization, process optimization, production process optimization, and other methods, which have nothing to do with BIW materials. Therefore, according to the current status of the automotive industry, the
utilization rate of various materials in the BIW stamping process is 55%.24

**Manufacturing and assembly stage.** The BIW is mainly composed of engine compartment assembly, roof, floor assembly, side wall assembly and rear wall assembly, mainly stamping parts. This study adopts one-mold, two-piece and three-sequence process. After the stamping parts are manufactured, they are assembled into BIW by welding.

The aluminum alloy used for BIW is 5000 Series and 6000 series, and the stamping process is also adopted. Similar to aluminum alloys, magnesium alloy components mainly use die-casting and stamping forming processes, and BIW components still use stamping forming methods. The materials used in the stamping process of BIW with four materials mainly include electric power, lubricating oil, liquid carbon dioxide, etc.6

Data statistics of welding and assembly processes are difficult. According to the research of University of California, Berkeley, the main energy consumption of automobile welding and assembly is: coating, air conditioning system & lighting, heating, material handling, welding, workshop compressed air, and other processes or equipment.25 In the assembly plant, except for the coal used in the heating process, all other processes are electric energy. The energy demand of each stage is shown in Table 3.

**Use stage.** BIW material is one of the main variables in this study. Therefore, the main research content is the influence of BIW material lightweight on the energy consumption of ICEV and BEV in this stage. According to research,26 the energy consumption shared by any component is approximately proportional to its mass, and its calculation formula is shown in equation (14).

\[
E_{uBIW} = k \times \frac{m_{BIW}}{M_{Vehicle}} \times E_{uVehicle} \tag{14}
\]

where \(E_{uBIW}\) is the energy consumption caused by the mass of the BIW in use; \(k\) is the allocation factor; \(m_{BIW}\) and \(M_{Vehicle}\) are the BIW mass and the curb mass of the vehicle, respectively; \(E_{uVehicle}\) is the total fuel consumption of the vehicle in use.

The value of \(k\) is quite controversial. Chen et al.12 took \(k\) as 1 in the life cycle assessment of vehicle seats, while Zackrisson et al.27 took \(k\) as 0.3 to study the life cycle of lithium battery for vehicles. According to the analysis of automobile theory,28 the energy consumption of vehicle and the quality of automobile are not linear positive correlation trends, but also affected by air resistance. Based on the research of Helms and Lambrecht,29 in this study, \(k\) value is taken as 4%.

Different from the gasoline consumption of ICEV, the electric power consumed by BEV has energy loss through the grid, charger and battery. Therefore, the consumption of electrical energy in the use phase also needs to consider the transmission efficiency of the power grid, the efficiency of the charger, and the efficiency of battery charging and discharging, as shown in Table 4.

The price of electricity is set at 0.58 yuan/degree, and the price of gasoline is set at 6.7 yuan/liter.32

**Scrap recycling stage.** In this study, the recovery and regeneration process of BIW metal materials are mainly considered in the scrap recovery stage. The recovery utilization rate and regeneration energy consumption of four kinds of BIW metal materials are shown in Table 5. Direct emissions are ignored due to statistical difficulties.

The regeneration of waste steel generally adopts EAF (electric arc furnace) process. The recycling process of waste aluminum materials generally includes

### Table 3. The energy demand of each stage.

| Coating | Air conditioning system and lighting | Heating | Material handling | Welding | Workshop compressed air |
|---------|-------------------------------------|---------|------------------|---------|-------------------------|
| Electric energy (MJ/kg) | 2.72 | 2.18 | – | 0.45 | 0.61 | 0.9 |
| Thermal energy (MJ/kg) | – | – | 2.03 | – | – | – |

### Table 4. The efficiency of grid transmission, charger and battery charge and discharge.

| The efficiency of grid transmission | The efficiency of charger | The efficiency of battery charge and discharge |
|------------------------------------|---------------------------|-----------------------------------------------|
| References | 94.1% | 96% | 90% |
| China Power Enterprise Federation | Yin | Yin | Yin and Hammond and Hazeldine |

\[ E_{uBIW} = k \times \frac{m_{BIW}}{M_{Vehicle}} \times E_{uVehicle} \]
two types of reverberatory furnace and rotary furnace. Magnesium alloy scrap is generally smelted with power frequency induction furnace. The specific process is not the focus of this study, and will not be described in detail.

**Impact assessment**

For energy consumption, only the energy consumed during the entire life cycle of the product is considered, and the scarcity of energy is not considered. It reflects energy consumption to the greatest extent and avoids interference by other factors. For the environmental impact, the CML2001 model is adopted in this study. According to the classification principle of ecological index method and current hot issues, three environmental impact types of mid-point assessment and one environmental impact type of end-point assessment are selected: global warming potential (GWP), acidification potential (AP), photochemical smog potential (POCP), and human health damage potential (HTP), respectively. The characteristic factors are from Gabi database.

In order to compare the relative sizes of various types of environmental impacts, the CML2001 method was used to standardize the four types of environmental impacts. The standardized reference value comes from the GaBi database. In order to get the comprehensive value of environmental impact, it is necessary to weight the standardized results of four types of environmental impact to reflect the relative importance of various types of environmental impact. Different from most studies, AHP method is used to scientifically obtain the weight of various types of environmental impact in this study.

The principle of analytic hierarchy process (AHP) is to decompose the problem into different constituent factors, and to aggregate and combine the factors according to their interrelation and subordination, so as to form a multi-level analysis structure model. The steps of AHP method are shown in Figure 4.

According to the scale table of nine importance levels proposed by professor Saaty, the two elements are compared to get the importance scale results, forming the judgment matrix, as shown in equation (15).

| Materials            | Recovery rate/% | Electric energy/kWh | Nature gas/m³ | Coal/kg | crude oil/kg | Gasoline/kg | Diesel/kg |
|----------------------|-----------------|---------------------|---------------|---------|--------------|-------------|-----------|
| Low-carbon steel     | 91              | 0.5367              | 0.0010        | 0.0048  | 0.0287       | 0           | 0         |
| High-strength steel  | 91              | 0.5367              | 0.0048        | 0.0287  | 0            | 0           | 0         |
| Aluminum alloy       | 98              | 0.2211              | 0.0338        | 0       | 0            | 6.02E-5     | 0.0090    |
| Magnesium alloy      | 95              | 0.5                 | 0             | 0       | 0            | 0           | 0         |

**Table 5.** Recycling utilization rate and renewable energy consumption per kilogram of BIW material.\textsuperscript{33,34}

**Figure 4.** The steps of AHP method.
Standardized reference values and weights are shown in Table 6.

### Results

In this study, MATLAB is used to compile the calculation program, and the inventory data of the whole life cycle of the lightweight BIW material is substituted into the ICEV and BEV models for calculation.

#### Energy consumption analysis

It can be seen from the calculation that the influence of BIW material lightweight on the energy consumption of ICEV and BEV is shown in Figure 5.

It can be seen from Figure 5 that in terms of the whole life cycle, the total energy consumption of BIW made of various materials of ICEV is far higher than that of corresponding BEV. In terms of the recovery stage, the energy consumption gains are only slightly lower than the energy losses in the raw material acquisition stage, mainly since the BIW materials are all metal materials with high recovery and utilization rate.

In this study, the remaining material losses in the material processing process are included in the recovery flow, and the loss of materials in the closed-loop flow process is minimized. For ICEV, BIW lightweight can effectively reduce energy consumption. BIW with low-carbon steel material has the highest energy consumption and BIW with magnesium alloy material has the lowest energy consumption. But for BEV, BIW with low-carbon steel material has the highest energy consumption, but BIW with aluminum alloy material has the lowest energy consumption. Due to the high energy consumption in the use stage of ICEV, which weakens the influence of raw material acquisition stage, while the energy consumption in the use stage of BEV is low, the disadvantages of high energy consumption of magnesium alloy in the raw material acquisition stage are obvious. After the energy loss in the raw material acquisition stage and the energy gain in the recovery stage are offset, the energy loss in the manufacturing and assembly stage is very important. The detailed analysis of the whole manufacturing and assembly

| Types of environmental impact | Standardized reference | Weights (dimensionless) |
|-------------------------------|-------------------------|-------------------------|
| GWP                          | 4.22E + 13 kg, CO2-Eq   | 0.482897267             |
| AP                            | 2.39E + 11 kg, SO2-Eq   | 0.271953849             |
| POCP                         | 3.68E + 10 kg, Ethene-Eq| 0.156983859             |
| HTP                          | 2.58E + 12 kg, DCB-Eq   | 0.088165025             |

Figure 5. Influence of BIW material lightweight on energy consumption of ICEV and BEV.
process shows that Low-carbon steel, high-strength steel, aluminum alloy, and magnesium alloy mainly consider six processes in the manufacturing and assembly stages, namely, Coating, Air conditioning system & lighting, Heating, Material handling, Welding, Workshop compressed air and different materials consume the same proportion of energy in each process. In addition, it can be seen that coating is the process with the highest energy consumption, accounting for up to 31%.

**Environmental impact analysis**

According to the standardized values and weights in Table 9, the quantitative analysis results of the environmental impact can be obtained. Environmental impact has both payout and payoff. To carry out this process, a lot of materials must first be invested and increase the environmental impact, which is called environmental damage. However, from the perspective of resource exhaustion, much emissions can be saved in the scrap recovery stage, which is called environmental benefits (negative value for the indicator). The quantitative analysis of the environmental impact of the lightweight BIW materials on ICEV is shown in Figure 6.

It can be seen from Figure 6 that in terms of the full life cycle, the order of various environmental impact types of BIW other than BIW of magnesium alloy from large to small is GWP, AP, POCP, and HTP, respectively. The ranking of various environmental impact types of magnesium alloy BIW from large to small is AP, GWP, HTP, and POCP. In terms of each stage, the environmental impact of the four kinds of BIW are the highest in raw material acquisition stage, and the overall environmental impact of low carbon steel BIW and high-strength steel BIW in use stage is lower than that in manufacturing and assembly stage, while the use stage and manufacturing and assembly stage of aluminum alloy BIW and magnesium alloy BIW are relatively close. Because four kinds of BIW are all metal materials, their own recovery rate is high. In this study, the material loss in the material processing stage is considered. Through the closed-loop reflux, the consumption of the full life cycle of the material is minimized, and the environmental benefits brought by the scrap recovery stage are very obvious.

The quantitative analysis of the environmental impact of the lightweight BIW materials on BEV is shown in Figure 7.

It can be seen from Figure 7 that in terms of the full life cycle, different from ICEV, the environmental impact types of magnesium alloy BIW of BEV rank from large to small, just like the other three types of BIW, is GWP, AP, POCP, and HTP. In terms of each stage, like ICEV, the environmental impact of the four kinds of BIW on BEV are the highest in raw material acquisition stage. The environmental impact of all kinds of materials BIW on BEV in the use stage is significantly higher than that in the corresponding manufacturing and assembly stage, which is significantly different from that of traditional vehicles. In addition, as the same as the ICEV, the environmental benefits brought by the scrap recovery stage are very obvious.

The comparison of environmental impact of four BIW applications in ICEV and BEV is shown in Figure 8. Where (a) represents the standardized value of environmental impact, and (b) represents the
comprehensive value weighted according to China’s resource endowment, and the weight is based on AHP method.

It can be seen from Figure 8(a) that the standardization value of environmental impact of BEV is higher than that of ICEV, and GWP and AP account for a relatively high proportion. It can be inferred from the previous section that it is mainly due to the large environmental impact of BEV in use stage. High proportion of coal electricity in China’s power grid structure is the root cause. The comprehensive value of environmental impact of BEV is also higher than that of ICEV. The BIW of ICEV from low-carbon steel materials to magnesium alloy materials are 51.10%, 50.75%, 42.76%, and 48.91% of BEV, respectively.

Different regions in China have different resource endowments, resulting in different power structures. Although different power structures consume the same power, the amount of pollutants emitted is different. The proportion of national average power structure cannot simulate the actual situation of typical regions in China. Therefore, this study takes Shandong, Hubei, Xinjiang and Sichuan, which have representative power structures, as examples. Not only can we study the environmental impact of the BIW in the scenario that the power structure is becoming more and more cleaner in the future, but also the current environmental impact of typical regions in China. The power structure of Shandong, Hubei, Xinjiang and Sichuan is shown in Figure 9.

Taking the emission list of power structure in typical areas of China into the MATLAB calculation model, the comprehensive environmental impact values of
BIW for ICEV and BEV under different power structure scenarios can be obtained, as shown in Figure 10.

It can be seen from Figure 10 that, except for Sichuan, the comprehensive value of environmental impact of BIW for BEV is greater than that of ICEV. Whether the BIW for BEV has the advantage of reducing emissions is closely related to the cleanliness of the power structure.

**Economic analysis**

The traditional automobile economic evaluation is mostly from the perspective of consumers, comprehensively considering the purchase cost, use cost and disposal cost of the car, and evaluating the economic benefits of consumers. This study is different from the traditional research, starting from the life cycle stage of automobile, to explore the actual economic impact of lightweight BIW materials on the life cycle of ICEV and BEV, respectively, and the impact of BIW material lightweight throughout each stage of the life cycle. Previous studies have shown that,\(^1\) vehicle lightweight will have a great impact on the capacity design of the power battery and the power design of the drive motor, while the cost of the power battery and the drive motor is relatively high and its cost is closely related to the capacity and power respectively. Therefore, in order to simulate accurately, this study considers the influence of BIW material lightweight on power battery and drive motor. However, the impact of lightweight on the cost of engine and transmission is not clear, and the cost of powertrain in ICEV is not high compared with that of BEV. Therefore, this study does not consider the impact of lightweight on it temporarily. For the relationship between power battery capacity and vehicle mass, refer to Wang\(^3\) research. The relationship between power battery power and vehicle mass is calculated according to the formula given in Sun.\(^1\)

According to Table 7, the price of power battery and drive motor of BIW with different materials can be calculated. Based on the above data, the break-even analysis of the four kinds of BIW applied to ICEV and BEV is shown in Figure 11.

It can be seen from Figure 10 that, for ICEV, the original cost of BIW material lightweight has increased to varying degrees. In the subsequent use process, when the driving mileage is more than 13621.8, 40294.78, and 57721.96 km, the cost of high-strength steel BIW, aluminum alloy BIW and magnesium alloy BIW start to be lower than that of low-carbon BIW. When the driving mileage is more than 62750.26 and 71309.47 km, the...

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**Figure 9.** Power structure of typical areas in China.

**Figure 10.** Comprehensive values of environmental impact of ICEV and BEV under typical power structure.
The cost of aluminum alloy BIW and magnesium alloy BIW start to be lower than that of high-strength steel BIW. When the mileage is more than 76,250 km, the cost of magnesium alloy BIW starts to be lower than that of aluminum alloy BIW. Even if the cost of the engine and transmission is taken into account, the break-even point will not be changed.

For BEV, the original cost of BIW material lightweight still increases to varying degrees. When driving 78625.68, 24.2229.6, and 342805.15 km km respectively, the cost of high-strength steel BIW, aluminum alloy BIW, and magnesium alloy BIW start to be lower than that of low-carbon steel BIW. When driving 390867 and 427305.87 km, respectively, the cost of aluminum alloy BIW and magnesium alloy BIW start to be lower than that of high-strength steel BIW. When driving 447105.73 km, the cost of magnesium alloy BIW is lower than that of aluminum alloy BIW. In this study, the total life cycle mileage of ICEV and BEV is only 150,000 km. Therefore, only high-strength steel BIW and low-carbon steel BIW have break-even point. However, considering the secondary weight reduction brought by the lightweight of BIW, the rated capacity of battery and the maximum power of motor will be reduced, which will greatly reduce the cost of power battery and motor, so that the original cost of high-strength steel BIW, aluminum alloy BIW and magnesium alloy BIW is lower than that of low-carbon steel BIW, and the lighter the material, the higher the cost-effectiveness of the whole life cycle.

**PSI analysis**

**Decision matrix.** The decision matrix is the beginning of PSI analysis and is a mathematical expression of candidate materials and evaluation criteria. After the evaluation criteria and candidate materials are determined, a decision matrix can be established, as shown in Tables 8 and 9.

**Calculate the final preference index.** The calculation results are shown in Table 10.

According to the PSI analysis method, the closer the final preference index is to 1, the better the scheme is. Table 10 shows the final calculation results. For ICEV,

| Material of BIW        | Power battery capacity/kWh | Peak power of drive motor/kW |
|------------------------|-----------------------------|------------------------------|
| Low-carbon steel       | 45                          | 98.01                        |
| High-strength steel    | 44.26                       | 96.02                        |
| Aluminum alloy         | 31.07                       | 61.07                        |
| Magnesium alloy        | 30.27                       | 59.27                        |

**Table 7. Influence of BIW material weight on power battery capacity and drive motor power.**

![Figure 11](image)

Figure 11. the break-even analysis of the four kinds of BIW applied to ICEV and BEV (i) indicates that the power system (engine + transmission) is not considered; (ii) indicates considering the power system (engine + transmission); (i) means the power system is not considered (power battery + drive motor); (ii) means considering the power system (power battery + drive motor).
magnesium alloy BIW is the comprehensive optimal solution regardless of the power system, and the final preference index is 1. For BEV, Aluminum alloy BIW is the comprehensive optimal solution regardless of the power system, and considering the power system and ignoring the power system, the final preference index of aluminum alloy is 0.94791322 and 0.933283578, respectively. In addition, in the four cases, the low-carbon steel BIW is the worst solution, and BEV is worse than ICEV. In general, the final preference index of magnesium alloy BIW is the largest for ICEV, which is the comprehensive optimal solution, while the final preference index of aluminum alloy BIW is the largest for BEV, which is the comprehensive optimal solution.

Conclusion

(1) This study extends the system boundary to the scrap recycling stage, fully considers the energy, environmental and economic benefits brought by the scrap recycling stage, and is closer to the actual situation. Based on the full analysis of the closed-loop flow of materials throughout the life cycle of the BIW, the waste recycling in the material processing and manufacturing stage was considered, and finally a general 3E-PSI evaluation calculation model for the replacement of lightweight materials of components was constructed by combining 3E analysis with PSI analysis. This model mainly extends the existing 3E model from the following three aspects. One is that it can accurately evaluate the energy consumption, environmental impact and economy of the lightweight material substitution for various auto components throughout the full life cycle; the other is that the energy consumption, environmental impact or economy of auto components can be studied by process or by index, based on the research needs; the third is that for the material lightweight of auto components, in addition to the horizontal comparative study of the energy consumption, environmental and economic impacts of ICEV and BEV, the optimal
solutions of ICEV and BEV can also be explored vertically.

(2) Based on this model, four different types of BIW are applied to ICEV and BEV on the same platform of the same enterprise, and their energy consumption, environmental impact and economy are comprehensively evaluated. Based on the comparative analysis method, the influence of material lightweight on ICEV and BEV is explored. The results show that the energy consumption of ICEV decreases with the material lightweight of BIW, while that of magnesium alloy BIW is the lowest. Different from the ICEV, the energy consumption of BEV decreases first and then increases with the material lightweight of BIW, and the energy consumption of aluminum alloy BIW is the lowest. The comparative analysis found that the energy consumption of the BIW of the ICEV is significantly higher than that of the BEV in the use stage, which makes the advantage of lightweight in the use stage prominent, and makes up for the disadvantage of high energy consumption of the magnesium alloy in the current raw material acquisition stage and the low recovery rate in the scrap recycling stage. In terms of environmental impact, both ICEV and BEV decrease with the material lightweight of BIW. Comparative analysis reveals that the environmental impact of ICEV and BEV has significantly different in the use stage, and the environmental impact of four types of BIW applied to BEV is significantly higher than that of ICEV. The fundamental reason is that China’s power grid structure is not clean. Therefore, increasing the proportion of clean energy power generation is imminent. In terms of economy, the initial cost of BIW will increase in varying degrees with the improvement of lightweight level of material if the influence of lightweight on power system is not considered. With the increase in mileage, the life cycle cost of magnesium alloy BIW applied to ICEV is the lowest, while the life cycle cost of high-strength steel BIW applied to BEV is the lowest. If the impact of lightweight on the power system is considered, the cost of BIW applied to ICEV increases overall, but the break-even point remains unchanged. Due to the weight reduction, the cost of power batteries and drive motors has decreased significantly. The initial cost of BIW applied to BEV gradually decreases with the degree of weight reduction of materials, and there is no break-even point throughout the life cycle.

(3) This 3E-PSI model can comprehensively consider energy, environmental and economic impacts and obtain the optimal BIW material selection scheme. In addition, the impact of lightweight on the power system is further explored. It can be seen from the analysis that, regardless of the influence of power system, the magnesium alloy BIW is the optimal solution for ICEV, while the aluminum alloy BIW is the optimal solution for BEV.

Author contributions
Haifeng Fang gives the whole modeling idea. Zhensen Ding established the mathematical evaluation model, and completed the PSI analysis. Zhensen Ding contributed to drafting paper. Bin Liu conducted the interview and edited the paper. Haifeng Fang, Zhensen Ding, Bin Liu, Zhanhui Yao and Jinzhou Liu were in charge of the final version.

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