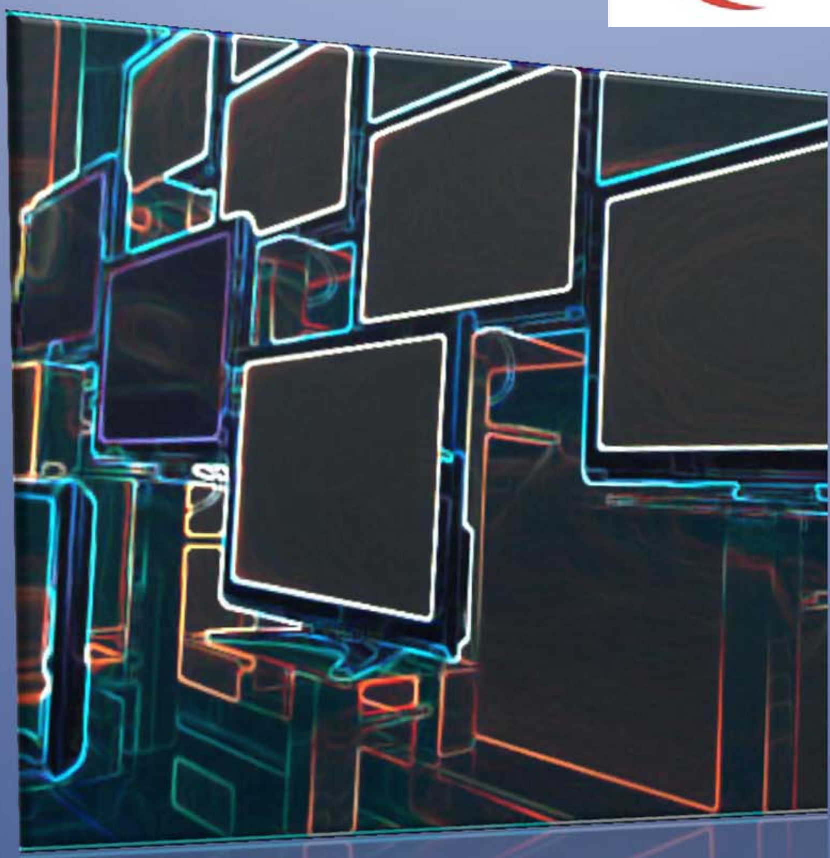

Product Carbon Footprint Standard Calculation Procedure for Display Industry

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World Display device Industry Cooperation Committee

WDICC Report

Product Carbon Footprint Standard Calculation Procedure for Display Industry

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Abstract

Life Cycle Assessment (LCA) is a powerful tool for distinguishing environmental impacts of different products and is generally recognized as a benchmark for prioritization of company's environmental aspects in products. This customized carbon footprint calculation standard is designed for products related to display industry. There are case studies for a 32inch module and a TV set by using the product carbon footprint calculation standard procedure. Most important of all, the result of the assessment can deal with the consistency, comparability and legitimacy for different products by using this standard and some suggestions are given at the end of this calculation standard.

Content

List of Figures

List of Tables

1 Product Carbon Footprint Calculation Standard for a TFT-LCD Module

1.1 Background

Nowadays, people are surrounded by ICT-related products and there are plenty of research topics arising after another. One of the research topic is product carbon footprint (PCF). PCF is one of the result category from life cycle assessment (LCA), and it can help designer to evaluate how much environmental impact of their product. However, when it comes to comparison of different product in the same level from different companies, there are so many problems, such as using different standards or databases, use stage and end-of-life stage are different from companies or countries, and so on, causing slice differences in results of the assessment from different products.

1.2 Goal and Scope

This product carbon footprint calculation standard is focus on upstream and midstream company of display industry, and the following content will be the necessary parts selected for product carbon footprint calculation for a TFT-LCD module. According to this standard, it can maintain the basic transparency in product carbon calculation and increase the comparability, accuracy and legitimacy between different products. Additionally, there is a database that can be used for the standard calculation, as shown in Appendix A. As a result, the goal of the assessment is to let designers know the difference among different product designs and find the emission hotspots, and deal with the problems in calculation and the result as mentioned above. The scope in the raw material stage is using different BOM from different primary company, and every company should at least provide scope1 and scope2 emissions after the greenhouse gas and reduction and management act.

1.3 System Boundary

Take a TV as a final product for example, the following figure is the typically system boundary for display industry, as shown in Figure 1. Some detailed information will be mentioned below.

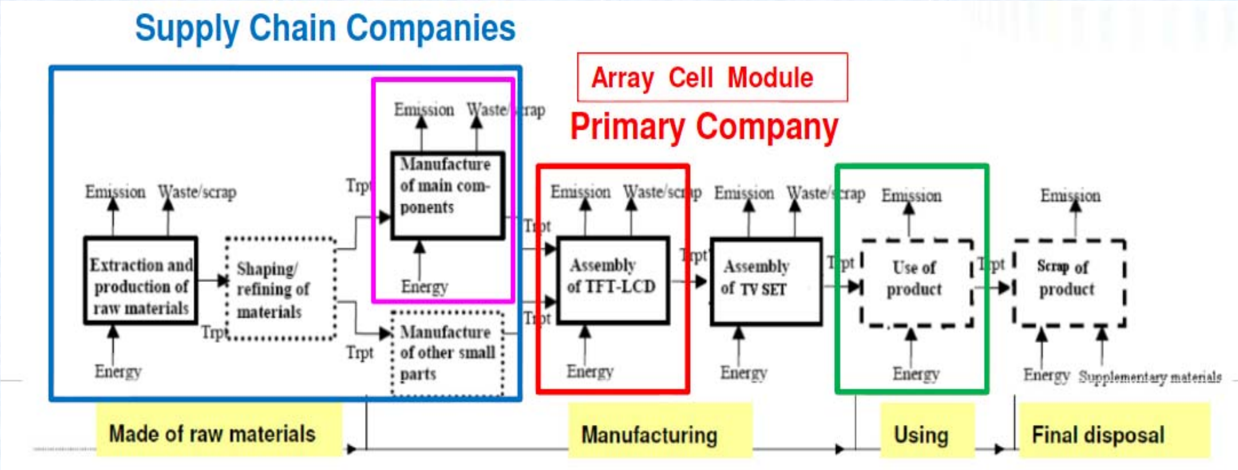

Figure 1. System boundary for display industry

1.4 Life Cycle Assessment of a TFT-LCD Module

1.4.1 Raw Material Stage

In raw material stage, a TFT-LCD module is comprised of some basic components and some supplementary materials for different manufacturing process. According to know-how protection of every company and keep the basic transparency of product carbon footprint calculation, the following parts are must be calculated in this stage, as shown in Table 1. Additionally, there are some allocation suggestions for upstream suppliers, as shown in Appendix C.

Table 1. Must be calculated in raw material stage

Process and Chemicals	Material and Components	Greenhouses Gases in GWP100
Array	Target ITO	
	Mo Target	
	Al Target	
	Glass	
Cell	AU Ball	
	Sealant	
	Power Seal	
	Polarizer	
	Liquid Polyimides	
	Liquid Crystal	
Color filter	Glass	
	ITO	
	BM	
	MVA	
	Color Resist	
	PS	
Module	PCBA	
	Driver IC	
	ACF	
	Bezel Front	
	Cushion Bezel Poron	
	Thermal Pad	
	Plate Shielding	
	Backlight unit	

Table 1. (Continued)

Process and Chemicals	Material and Components	Greenhouses Gases in GWP100
Module	Inverter	
	Plate diffuser	
	Sheet diffuser	
	Sheet DBEF	
	Sheet prism	
	Sheet reflector	
	Bezel back	
	Frame lower	
	Fame upper	
	Inverter cover	
	Lamp support	
	Lamp block (right)	
	Lamp block (left)	
	Tape	
	Label	
	Rubber	
	Screw	
	Connector	
	Cable	
	CCFL	
Supplementary material	Aluminum etch	
	EBR	
	Developer	
	Stripper	
	Nitrogen trifluoride (NF_3)	
	Photo resist	
	NMP	
	Oxalic acid	
	Isopropyl alcohol	
	Nitrous oxide(N_2O)	

Table 1. (Continued)

Process and Chemicals	Material and Components	Greenhouses Gases in GWP100
Supplementary material	Oxygen	
	Argon	
	Carbon dioxide (CO_2)	
	Hydrogen	
	Helium gas	
	Ammonia	
	Chlorine	
	Sulfur hexafluoride (SF_6)	
	Ethanol	
	Acetone	
	PH_3/H_2	
	Thinner	
	Soda buffer solution	
	Hydrogen peroxide	
	Sodium bisulfite	
	Sodium hypochlorite	
	Sodium hydroxide	
	Polymer	
	Poly aluminum chloride (PAC)	
	Calcium chloride	
	Sulfuric acid	
SUM		$kgCO_2eq$

Note: *As for display industry, a TFT-LCD module usually contains the drive circuits (Drive ICs), while a TFT-LCD panel for special customer does not contain the drive circuits.*

Speaking of the need to include supplementary materials in the raw material stage, there are some common greenhouse gases that should be aware of the usage, such as carbon dioxide (CO_2) and nitrous oxide (N_2O). Most primary company has their own recycling plan for those common greenhouse gases, as a result, the actual usage of some common greenhouse gases are different from the information in the BOM after the recycling plan from different primary company. Furthermore, some other special gases called fluorinated compounds (FCs), namely nitrogen trifluoride (NF_3) and sulfur hexafluoride (SF_6), are extremely powerful greenhouse gases that IPCC has announced strict emission and recycling regulations on them. Hence, every primary company is obligated for buying special machines to deal with the recycling regulations of special gases, and IPCC has proposed some standard calculation methods to estimate the carbon footprint emissions for those powerful greenhouse gases after special recycling process. However, it is mentioned that principle of protection is considered for every company in the standard calculation procedure. According to using limited information in the BOM to know merely each usage of supplementary material, Tier 2a method followed by the decision tree from IPCC, as shown in Figure 2, is going to be use for estimation of carbon footprint emission in the raw material stage [1]:

$$\mathbf{E_i = (1-h) x FC_i x (1-U_i) x (1-a_i \, x \, d_i) x GWP_i}$$

where

E_i = emission of gas, kg

FC_i = consumption of gas i, (e.g., CF_4, C_2F_6, C_4H_6, C_5F_8, CHF_3, NF_3, SF_6)

h = fraction of gas remaining in shipping container (heel) after use, fraction

U_i = use rate of gas $_i$ (fraction destroyed or transformed in process), fraction

a_i = fraction of gas i volume used in processes with emission control technologies (company- or plant- specific), fraction

d_i = fraction of gas i destroyed by the emission control technology, fraction

GWP_i = global warming potential value of gas i

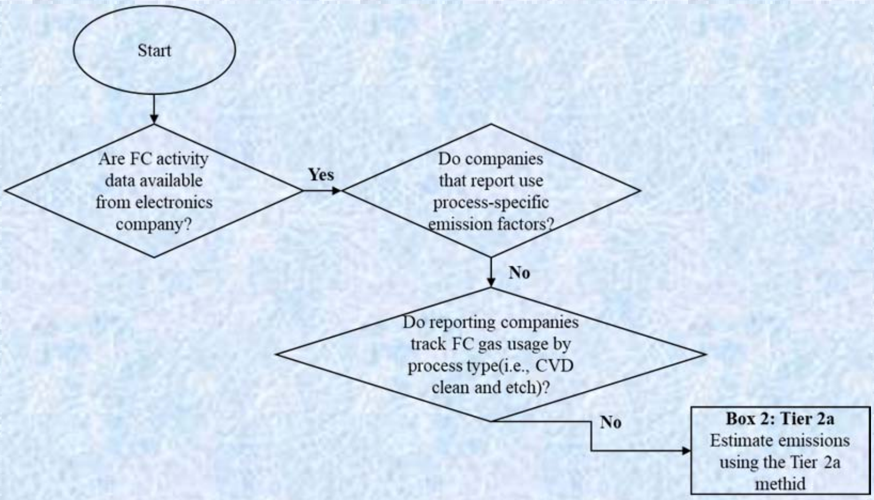

Figure 2. The decision tree for the Tier 2a method from IPCC [1]

Because of the strict regulations of recycling for special machines, there are recycling functions of destruction and recovery efficiency standard parameters for special gases. Different primary company will buy different machines that have different recycling functions from different company for the environmental regulations. However, those machines should all have the basic ability to meet with environmental regulations. To put it another way, the input usage of special gases which vary from different primary company are not real in the BOM, and standard calculation methods which provide default emission factors from IPCC are going to estimate real emissions after special processes from special machines for different primary company, as shown in Table 2.

Table 2. Default emission factors for FC emissions from LCD manufacturing [1]

	Nitrogen trifluoride (NF_3)	Sulfur hexafluoride (SF_6)
h	0.1	0.1
U_i	0.8	0.8
a_i	0.9	0.9
d_i	0.95	0.9
GWP	16100	23500

However, new technologies change over time. The basic components and some chemicals in the raw material will vary with new technologies. The parts in the Table 1 is selected from an old module in 2009. As a result, this table for raw material stage may not reflect the reality of a present module. It needs the help form Taiwan TFT LCD Association (TTLA) to let every company in Taiwan to discuss about what new materials and chemicals should be listed over time in raw material stage. Furthermore, every company is obligated to do carbon footprint analysis on new materials or chemicals when there is any new material or chemical being used in the new manufacturing process. If new materials or chemicals have large amount in the manufacturing process or high carbon footprint emission factors, they should list them into raw material stage including the must calculated parts.

1.4.2 Manufacturing Stage

There are three main processes for manufacturing TFT-LCD modules: Array (+Color Filter), Cell, and Module. Typical manufacturers will put the array process and cell process in one facility and perform module assembly in another. The reason is that array process and cell process are technological-intensive processes which means high consumption of electricity power and requirement for different unique chemicals, while module assembly process is a labor-intensive process which assembles other components to fabricate TFT-LCD modules for shipping to the downstream companies, such as manufactory of TVs, cell phones, and so on.

The array and cell facilities take in large pieces of glass, and there are pieces of glass typically cut in the beginning of the module process. The size of the incoming piece of glass is dependent on the generation of the plant and generation refers to each glass size that can be handled within a specific facility. Consequently, the total manufacturing carbon footprint equation for a TFT-LCD module is as follow [2]:

MCF_{LCDM} (kg CO_2 eq) = [(GHG_F/A_{input}) x ($A_{LCDM}+A_{scrap}$)]

where

MCF_{LCDM} = the manufacturing carbon footprint of a single LCD module (kg CO_2 eq)

GHG_F = the total manufacturing facility greenhouse gas emission in a year (kgCO_2 eq)

A_{input} = the total input glass area (for TFT and color filter) brought into the facility in a year (in m^2)

A_{scrap} = the area of glass scrap (will be a function of the generation and display area)

Note. *scrap may not be relevant for module assembly*

A_{LCDM} = the total area of a specific LCD (in m^2)

Besides, the primary company should follow the GHG protocol corporate accounting and reporting standard to perform a GHG emissions inventory. However, it has only to include Scope1 and Scope2 emissions for GHG emissions inventory. Because the range of Scope3 emissions is usually too extensive to include in GHG emissions inventory. In contrast to Scope 1 and Scope2 emissions, they are both clear enough to easily include in GHG emissions inventory for further analysis, as shown in Table 3.

Table 3. Definitions of Scope1, Scope2 and Scope3 [3]

Scope 1	Scope 2	Scope 3
Direct GHG emissions	Electricity indirect GHG emissions	Other indirect GHG emissions

1.4.3 Transportation Stage

According to the peculiarities of display industry mentioned above, the array and cell facilities are in the same place for the reason of technological-intensive processes, and module assembly facilities are in another place for the reason of labor-intensive process, as shown in Figure 3. Due to lower the cost of products, labor-intensive process will often be moved to low-cost countries. In transportation stage, we need to beware of the location of the facility and calculate according to which type of transportation. In addition, it is mandatory for supply chain companies to offer the actual ways of transportation for shipping components or materials to the primary company.

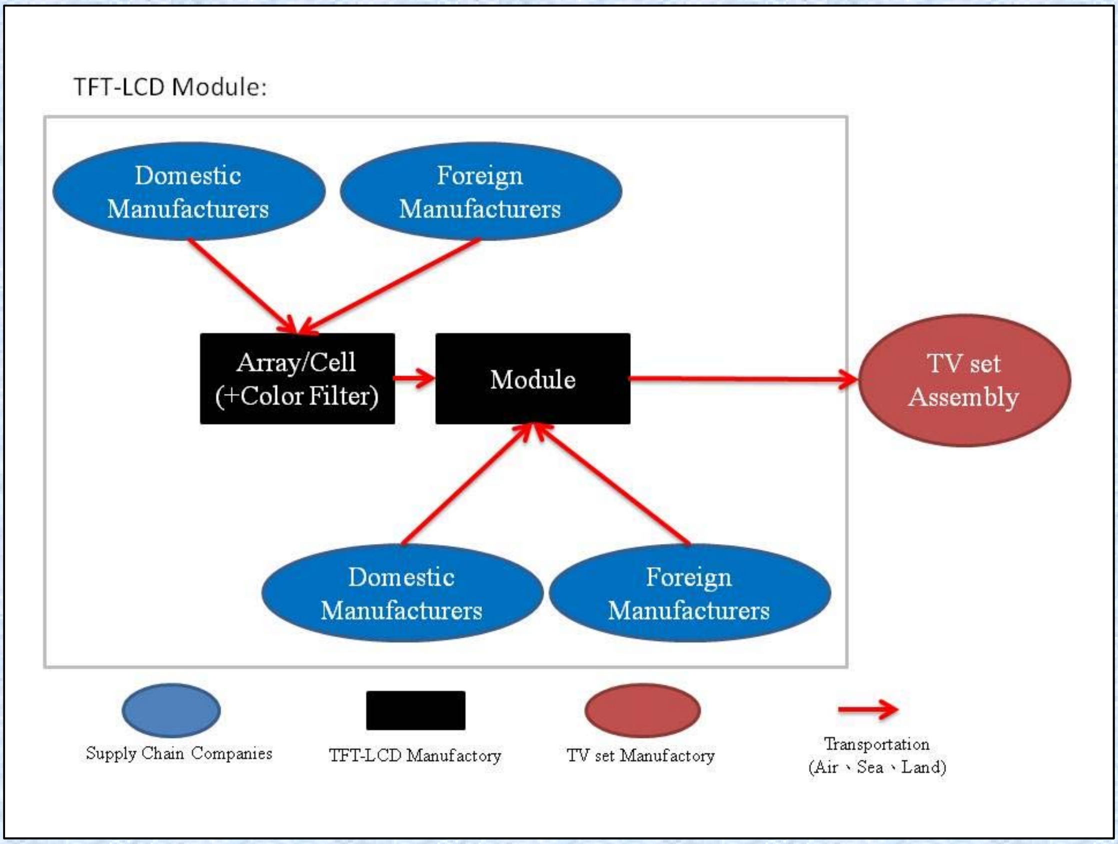

Figure 3. Logistics status of the display industry

1.4.4 Product Carbon Footprint of a TFT-LCD Module

- B2B type : A TFT-LCD module is a B2B product, for example so the product carbon footprint only includes raw material stage, manufacturing and transportation stage. After adding up the result of these three stages, it will be the product carbon footprint of a TFT-LCD module, as shown in Table 4.

Table 4. Product carbon footprint for a TFT-LCD module

A TFT-LCD Module (B2B)	Raw materials Stage	Manufacturing Stage	Transportation Stage	SUM
	A kg CO_2 eq	B kg CO_2 eq	C kg CO_2 eq	A+B+C kg CO_2 eq

- B2C type : When a TFT-LCD module, as a raw material, is shipping to the downstream company such as TV manufactory, a TV will become a B2C product and there is a standard scenario for use stage calculation, as shown in Table 5. Additionally, there is a case study of a TV, as shown in Appendix B. Furthermore, there are still many products related to modules and there are standard scenarios collected from public researches or statistics for use stage, as shown in Table 6 to Table 8.

Table 5. Standard use stage scenario for TVs [4]

TV use stage standard scenario	On mode (hours/day)	Stand-by mode (hours/day)	Off mode (hours/day)	Use day per year (days/year)	Life time (years)
	4	20	0	365	6.6

Table 6. Standard use stage scenario for Desktops [4]

Desktop use stage standard scenario	Type	On mode (hours/day)	Stand-by mode (hours/day)	Off mode (hours/day)	Use day per year (days/year)	Life time (years)
	Home	4	8	12	365	6.6
	Office	6	9	9	365	6.6

Table 7. Standard use stage scenario for Laptops [4]

Laptop use stage standard scenario	Type	On mode (hours/day)	Stand-by mode (hours/day)	Off mode (hours/day)	Use day per year (days/year)	Life time (years)
	Home	4	8	12	365	5.6
	Office	7	8	9	365	5.6

Table 8. Standard use stage scenario for Smart phones [5]

Smart phones use stage	On mode (hours/day)	Stand-by mode (hours/day)	Off mode (hours/day)	Use day per year (days/year)	Life time (years)
standard scenario	5	19	0	365	4.7

2 Conclusion

In this product carbon footprint standard calculation procedure, there are two following suggestions. First, there is a selection problem in raw material stage. Due to ICT-related product changing rapidly, the processes and materials will change accordingly, such as the present type of backlight in the TFT-LCD module is LED, not CCFL. Besides, there are different types of LCD module for final products. This standard calculation procedure used the dominant module, TFT-LCD module, to be the main content. Therefore, this standard should be changing rapidly for reality by TTLA, and there should be another analysis to discuss about different type of LCD module. Second, there are lots of ICT-related products for TFT-LCD modules, such as cell phones, tablets, laptops and so on, which have different use stage scenarios and end-of-life scenarios. Hence, each of ICT-related product for use stage scenario calculation should be unified separately and every company should design for their end-of-life strategies for their product in order to cater to reality. In the future, this standard will promote product carbon footprint calculation automatically.

3 Acknowledgements

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5 Emission Factor Database for Display Industry (Appendix A)

5.1 Foreword

Manufacturing LCD modules require a lot of materials from supply chain company for complex processes. If primary company want to calculate product carbon footprint for LCD modules, it is often to find emission factor from different databases or LCA software for different material. However, most of databases and LCA software are well-developed in Europe but supply chain companies for display industry are located in Asia such as Taiwan, Japan, Korean, and China. Therefore, it is always a big problem to find the corresponding emission data in those databases and LCA software from Europe. For this reason, there is another aim, emission factor database for display industry, as important as the carbon footprint standard calculation. This reference database for display industry is organized from present companies who has completed their own product carbon footprint assessment for their products in 2009. If some primary companies who don't have emission factor from supply chain companies want to calculate their product carbon footprint for their own LCD module, this database can be used for their calculation.

5.2 Database for Display Industry (for Primary Company)

5.2.1 Introduction

This database is classified into six tables according to the peculiarities for display industry, as shown in Table 9 to Table 14, including Array Process, Cell Process, Color Filter Process, Module Process, Package and Supplementary Materials, respectively. Primary companies can choose emission factors of related parts from their own LCD module design to calculate carbon footprint of their LCD module in raw material stage. Furthermore, most of the data are from a Taiwanese company who has done their inventory analysis and some of the data source are from some databases such as Ecoinvent, ETH-ESU96, and IDEMAT2001, or LCA software such as Simapro7.1.

If LCD modules offer to the downstream company like TV set manufactory, there are also related database for carbon footprint of TV set in raw material stage that can be used, as shown in Table 15.

5.2.2 Database for Primary Company

Table 9. Array process emission factor

Process	Parts	Emission Factor (kgCO_2eq/kg)
Array	Target ITO	119.11
	Mo target	10.16
	Al target	2.53
	Glass	4.40

Table 10. Cell process emission factor

Process	Parts	Emission Factor (kgCO_2eq/kg)
Cell	AU ball	6687.50
	Sealant	5.31
	Power seal	2.70
	Polarizer	55.89
	Liquid polyimide	22.67
	Liquid crystal	2.02

Table 11. Color filter process emission factor

Process	Parts	Emission Factor (kgCO_2eq/kg)
Color filter	Glass	4.40
	ITO	85.61
	BM	2.17
	MVA	5.05
	Color resist	3.03
	PS	0.66

Table 12. Module process emission factor

Process	Parts	Emission Factor (kgCO_2eq/kg)
Module	PCBA	228.57
	Driver IC	1990.63
	ACF	60.14
	Bezel front	4.16
	Tape	7.65

Table 12. (Continued)

Process	Parts	Emission Factor (kgCO_2eq/kg)
Module	Cushion bezel poron	170.00
	Thermal pad	5.13
	Plate shielding	38.62
	Screw	88.75
	Backlight unit	Lack of data
	Inverter	300.63
	Plate diffuser	10.85
	Sheet diffuser	2.71
	Sheet DBEF	2.59
	Sheet prism	7.34
	Sheet reflector	11.00
	Bezel back	3.63
	Frame lower	9.45
	Fame upper	9.59
	Inverter cover	11.67
	Lamp support	14.66

Table 12. (Continued)

Process	Parts	Emission Factor (kgCO_2eq/kg)
Module	Lamp block (right)	8.75
	Lamp block (left)	8.75
	Label	14.70
	Rubber	20.38
	Connector	172.09
	Cable	332.50

Table 13. Package process emission factor

Process	Parts	Emission Factor ($kgCO_2eq/kg$)
Package	Label	13.40
	Film protect	2.75
	Crepe paper tape	1.24
	Bag anti-static	2.14
	Cushion packing	0.31
	Packing carton	0.32
	OPP	Lack of data

Table 14. Supplementary material emission factor

	Parts	Emission Factor ($kgCO_2eq/kg$)
Supplementary material	Aluminum etch	1.60
	EBR	2.05
	Developer	0.06
	Stripper	2.61
	Nitrogen trifluoride (NF_3)	16100 [6]
	Photo resist	1.36
	NMP	Lack of data

Table 14. (Continued)

	Parts	Emission Factor (kgCO_2eq/kg)
Supplementary material	Oxalic acid	Lack of data
	Isopropyl alcohol	3.19
	Nitrous oxide (N_2O)	265 [6]
	Oxygen	0.41
	Argon	0.31
	Carbon dioxide	1 [6]
	Hydrogen	1.66
	Helium gas	0.93
	Ammonia	2.12
	Chlorine	0.88
	Sulfur hexafluoride (SF_6)	23500 [6]
	Ethanol	0.33
	Acetone	2.22
	PH_3/H_2	1.66
	Photo resist	3.25
	Thinner	3.55

Table 14. (Continued)

	Parts	Emission Factor (kgCO_2eq/kg)
Supplementary material	Soda buffer solution	1.22
	Hydrogen peroxide	1.21
	Sodium bisulfite	Lack of data
	Sodium hypochlorite	0.92
	Sodium hydroxide	1.24
	Sulfuric acid	0.14
	Polymer	Lack of data
	Calcium chloride	0.89
	Hydrogen Peroxide	1.21
	Poly aluminum chloride (PAC)	Lack of data

Table 15. TV set related emission factor

	Category	Parts	Emission Factor ($kgCO_2eq/kg$)
TV set	Base assembly	Plastic cover	3.87
		PE bag	2.12
		Rubber	241.48
	Cover rear assembly	Cover rear plastic	4.48
		Tape anti-noise	Lack of data
		Sponge left	16.25
		Sponge right	2.93
		Rubber	2.28
	Bezel Front assembly	Bracket	9.48
		Film protect	2.53
		Bezel plastic	3.87
		Plastic cover	86.00
		Tape anti-noise	9.50
		Rubber	2.28
		Nut	5.51
	Others	Neck set	3.28
		BOX	33.55

Table 15. (Continued)

	Category	Parts	Emission Factor (kgCO_2eq/kg)
TV set	**Others**	Plastic cover	14.71
		Fix tape	2.28
		Screw	104.93
		Cable Assembly	100.84
		Bracket	1.87
	Package	Bag	2.02
		Tape	0.23
		Carton	0.33
		Product label	2.10
		Characteristic label	981.40
		Other label	690.70
		Serial number label	0.30
		Cushion packing	Lack of data

5.2.3 Summary

In this database, there are some parts that still don't have emission factors and some of the data is no longer be used in display industry, such as CCFL due to the ICT-related materials changing rapidly. The type of backlight unit, LED, is substituted for CCFL in present display industry. Therefore, it is important to update this database from different display industry. This database can not only help primary company calculate their product carbon footprint about their design but push their supply chain company to do the inventory analysis. In the future, this database is going to be completed and the further level is to let every company have a related reference to compare their product with others.

5.3 Database for Display Industry (for Supply Chain Company)

5.3.1 Introduction

As for the supply chain companies, there is another database which is chosen from Ecoinvent because it was one of the most popular database and widely used in the world. However, the data of electricity from Taiwan, China, Japan, Korea and global world in Ecoinvent are replaced in this standard database. For fuel of energy item, we replaced the data in Ecoinvent by the inventory results of companies in display industry. The database of carbon footprint emission factor is proposed to classify into 4 different level of classification, such as primary category, secondary category, minor category, and small sub-category. There are 12 items in primary category, such as Metal, Plastic, Chemical, Paper, Wood, Glass, Ceramic, Grease, Electronics, Energy, Transportation, and Waste, as shown in Table 16, and some items are only have classified into primary category and secondary category. The small sub-category only exists in the primary category "Electronics", as shown in Table 17.

Table 16. Example of classification (Partial list)

<table>
<tr><th>Primary Category</th><th>Secondary Category</th><th>Minor Category</th><th>Small Sub-Category</th></tr>
<tr><td rowspan="8">Metal</td><td rowspan="4">Ferro</td><td>Cold-rolled steel plate</td><td></td></tr>
<tr><td>Electrogalvanized steel plate</td><td></td></tr>
<tr><td>Galvanized steel plate</td><td></td></tr>
<tr><td>Iron</td><td></td></tr>
<tr><td rowspan="4">Non-Ferro</td><td>Aluminium (Al)</td><td></td></tr>
<tr><td>Cadmium (Cd)</td><td></td></tr>
<tr><td>Chromium (Cr)</td><td></td></tr>
<tr><td>Copper (Cu)</td><td></td></tr>
<tr><td rowspan="3">Plastic</td><td rowspan="3">Plastic</td><td>ABS (Acrylonitrile-Butadiene-Styrene)</td><td></td></tr>
<tr><td>PE(Polyethylene)</td><td></td></tr>
<tr><td>LDPE (Low density polyethylene)</td><td></td></tr>
<tr><td rowspan="2">Chemical</td><td>Magnesium oxide</td><td></td><td></td></tr>
<tr><td>Manganese oxide</td><td></td><td></td></tr>
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<tr><td>Wood</td><td></td><td></td><td></td></tr>
<tr><td>Glass</td><td>Glass</td><td>Glass</td><td></td></tr>
<tr><td>Ceramic</td><td></td><td></td><td></td></tr>
<tr><td>Grease</td><td></td><td></td><td></td></tr>
</table>

Table 16. (Continued)

Primary Category	SecondaryCategory	Minor Category	Small Sub-Category
Electronics	Chip Resistor	Metal	Lead(Pb,Plumbum)
Energy	Electricity		
	Gasoline&Petrol		
Transportation	Aircraft		
	Truck,Lorry		
Waste	Recycling		
	Landfill		

Table 17. Example of small sub-category in the primary category "Electronics"

Primary Category	Secondary Category	Minor Category	Small Cub-Category
Electronics	Chip Resistor		
		Resistor	
		Metal	
			Lead(Pb,Plumbum)
			Silver(Ag)
			Nickel(Ni)
			Tin(Sn,Stannum)
			Palladium(Pd)

5.3.2 Database for Supply Chain Company

The following four tables are most relevant to display industry, as shown in Table 18, Table 19, Table 20 and Table 21. In the table, "Primary Category" is the highest level in the classification rule, "Secondary Category" is the lower level than "Primary Category", "ID" is the ID code of the Ecoinvent, "Name in Ecoinvent V2.2"is the related name in the Ecoinvent V2.2,"Unit"is the unit for produce carbon footprint, such as kg, m^2, or m^3, and "Emission Factor" is the numerical value of unit of equivalent carbon emission per substance (such as $kgCO_2eq/kg$).

Table 18. Metal related emission factor

Primary Category – Metal					
Secondary Category	**Minor Category**	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Ferro	Cold-rolled steel plate	*	steel sheet, cold rolled	kg	2.124
	Electrogalvanized steel plate		**		
	Ferrochrome(Ferrochromium)	1095	Ferrochromium, high-carbon, 68% Cr, at plant/GLO U	kg	1.91
	Ferromanganese	1097	ferromanganese, high-coal, 74.5% Mn, at regional storage/RER U	kg	0.973
	Ferronickel	1098	Ferronickel, 25% Ni, at plant/GLO U	kg	9.23
	Ferrosilicon	*		kg	6.5455
	Galvanized steel plate		Galvanized steel sheet, at plant/RNA	kg	2.71
	Hot-rolled steel plate		Hot rolled sheet, steel, at plant/RNA	kg	2.3
	Iron	1069	Cast iron, at plant/RER U	kg	1.48

Table 18. (Continued)

Primary Category – Metal					
Secondary Category	**Minor Category**	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Ferro	Non-electroplated steel		**		
	Painted steel plate	*		kg	2.309
	Stainless steel plate	*		kg	1.8393
	Ferrite	7090	Ferrite, at plant/GLO U	kg	1.49
Non-Ferro	Aluminium	1054	Aluminum, primary, at plant/RER U	kg	12.2
	Cadmium	7163	Cadmium, primary, at plant/GLO U	kg	0.8
	Chromium	1073	Chromium, at regional storage/RER U	kg	26.7
	Copper	1088	Copper, primary, at refinery/RAS U	kg	4.75
	Brass	1066	Brass, at plant/CH U	kg	2.45
	Bronze	1068	Bronze, at plant/CH U	kg	2.77
	Lead(Pb,Plumbum)	10777	Lead, primary, at plant/GLO U	kg	2.11
		10150	Lead, secondary, at plant/RER U	kg	0.652

Table 18. (Continued)

Primary Category – Metal					
Secondary Category	**Minor Category**	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Non-Ferro	Magnesium (Mg)	1106	Magnesium, at plant/RER U	kg	73.7
	Nickel (Ni)	1121	nickel, 99.5%, at plant/GLO U	kg	10.8
	Niobium (Nb)		**		
	Tin-plated steel plate	7125	tin plated chromium steel sheet, 2 mm, at plant/RER U	m^2	82.2
	Tin (Sn,Stannum)	1155	tin, at regional storage/RER U	kg	17.1
	Titanium (Ti)	*		kg	45.0918
	Solder	1148	Soft solder, Sn97Cu3, at plant/RER U	kg	15.9
		10782	Solder, bar, Sn63Pb37, for electronics industry, at plant/GLO U	kg	11.4
		10784	Solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant/GLO U	kg	20.5

Table 18. (Continued)

Primary Category – Metal					
Secondary Category	**Minor Category**	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Non-Ferro		10783	Solder, paste, Sn63Pb37, for electronics industry, at plant/GLO U	kg	17.2
		10785	Solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry, at plant/GLO U	kg	26.3
		1067	Brazing solder, cadmium free, at plant/RER U	kg	2.58
	Zinc (Zn)	1156	Zinc, primary, at regional storage/RER U	kg	3.38
	Silver (Ag)	10153	Silver, at regional storage/RER U	kg	100
	Gold (Au)	10121	Gold, at regional storage/RER U	kg	13100
	Cobalt (Co)	5836	Cobalt, at plant/GLO U	kg	8.27
	Palladium (Pd)	1127	Palladium, at regional storage/RER U	kg	9720
		1129	Palladium, primary, at refinery/RU U	kg	9720
		1128	Palladium, primary, at refinery/ZA U	kg	10600
		1130	Palladium, secondary, at refinery/RER U	kg	758

Table 18. (Continued)

Primary Category – Metal					
Secondary Category	**Minor Category**	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Non-Ferro	Manganese (Mn)	1109	Manganese, at regional storage/RER U	kg	2.59
	Platinum (Pt)	1133	Platinum, at regional storage/RER U	kg	14800
		1135	Platinum, primary, at refinery/RU U	kg	14500
		1134	Platinum, primary, at refinery/ZA U	kg	15800
	Gallium (Ga)	6908	Gallium, semiconductor-grade, at plant/GLO U	kg	205
		6909	Gallium, semiconductor-grade, at regional storage/RER U	kg	210
	Mercury (Hg)	1111	Mercury, liquid, at plant/GLO U	kg	12.1
	Silicon (Si)	*		kg	5.4321
	Molybdenum (Mo)	1116	Molybdenum, at regional storage/RER U	kg	7.61
	Galvanized steel plate		Galvanized steel sheet, at plant/RNA	kg	2.71
	Arsenic (As)		**		
	Barium (Ba)		**		

Table 18. (Continued)

Primary Category – Metal					
Secondary Category	**Minor Category**	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Non-Ferro	Antimony (Sb)	11162	Antimony, at refinery/CN U	kg	12.9
	Selenium (Se)		**		
	Vanadium (V)		**		
	Tungsten (W)		**		
	Calcium (Ca)		**		
	Strontium (Sr)		**		

Note. *Table 18**:** * is not from Ecoinvent V2.2; ** is related data in the category but there is no corresponding information for emission factor.*

Table 19. Plastic related emission factor

Secondary Category	Minor Category	ID	Name in EcoinventV2.2	Unit	Emission Factor
Primary Category - Plastic					
Plastic	ABS (Acrylonitrile-Butadiene-Styrene)	1817	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER U	kg	4.39
	Acrylic		**		
	AS (Styrene-Acrylonitrile, SAN)	1846	styrene-acrylonitrile copolymer, SAN, at plant	kg	4.06
	Epoxy (or Epoxy Resin)		Liquid epoxy resins E	kg	8.25
	Foam polystyrene		Expandable polystyrene (EPS) E	kg	3.38
	Hard urethane	1839	Polyurethane, rigid foam, at plant/RER U	kg	4.31
	Soft urethane	1838	Polyurethane, flexible foam, at plant/RER U	kg	4.84
	Urethane	*		kg	4.575
	PS (Polystyrene)		General purpose polystyrene, at plant/RNA	kg	2.7
	PS-H	1837	Polystyrene, high impact, HIPS, at plant/RER U	kg	3.5

Table 19. (Continued)

Primary Category - Plastic					
Secondary Category	**Minor Category**	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Plastic	PE (Polyethylene)	1820	fleece, polyethylene, at plant	kg	2.86
	LDPE (Low Density Polyethylene)	1830	polyethylene, LDPE, granulate, at plant/RER U	kg	2.1
	LLDPE (Linear Low Density Polyethylene)	1831	polyethylene, LLDPE, granulate, at plant/RER U	kg	1.85
	HDPE (High Density Polyethylene)	1829	polyethylene, HDPE, granulate, at plant/RER U	kg	1.93
	PA6 (Polyamide 6)	1821	Nylon 6, at plant/RER U	kg	9.27
	PA12 (Polyamide 12)		**		
	PA66 (Polyamide 66)		Nylon 66, at plant/RER U	kg	8.01
	PC(Polycarbonate)	1826	polycarbonate, at plant/RER U	kg	7.78
	PC-ABS	**		kg	6.085
	PBT (Polybutylene Terephthalate)		**		

Table 19. (Continued)

Primary Category - Plastic					
Secondary Category	**Minor Category**	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Plastic	PET (Polyethylene Terephthalate)		Polyethylene terephthalate (PET) granulate, production mix, at plant, amorphous RER	kg	3.27
	PMMA (Acrylic resin, Polymethyl Methacrylate)		Polymethyl methacrylate(PMMA)beads, production mix, at plant RER	kg	7.05
	Polyoximethylene		**		
	POM (Polyfounoldehyde ResinPolyox Mothylene Resin)		**		
	PP(Polypropylene)	1834	Polypropylene, granulate, at plant/RER U	kg	1.97
	PPE(Polyphenylene)		**		
	PVC (Polyvinyl Chloride or PolyvinylChloride)	1840	Polyvinylchloride, at regional storage/RER U	kg	2.01
	SBR (Styrene Butdiene Rubber)	1847	Synthetic rubber, at plant/RER U	kg	2.65
	Polyphenylene sulfide(PPS)	11123	Polyphenylene sulfide, at plant/GLO U	kg	5.55

Note. *Table 19**:** * is not from Ecoinvent V2.2; ** is related data but there is no corresponding information.*

Table 20. Energy related emission factor

Primary Category - Energy				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Electricity (No transmission loss)	*	Electricity, Taiwan	KWH	0.612
	*	Electricity, China, Huabei	KWH	0.7495
	*	Electricity, China, Dongbei	KWH	0.7086
	*	Electricity, China, Huadong	KWH	0.6789
	*	Electricity, China, Huazhong	KWH	0.4543
	*	Electricity, China, Xibei	KWH	0.6878
	*	Electricity, China, Huanan	KWH	0.4506
	*	Electricity, China, Hainan	KWH	0.7328
	*	Electricity, Canada,	KWH	0.181
	*	Electricity, Mexico,	KWH	0.44
	*	Electricity,United States(US)	KWH	0.535
	*	Electricity,Australia,	KWH	0.883
	*	Electricity, Japan (JP)	KWH	0.436

Table 20. (Continued)

Primary Category - Energy				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Electricity (No transmission loss)	*	Electricity, Korea	KWH	0.459
	*	Electricity, New Zealand	KWH	0.214
	*	Electricity, Austria (AT)	KWH	0.183
	*	Electricity, Belgium (BE)	KWH	0.249
	*	Electricity, Czech Republic (CZ)	KWH	0.544
	*	Electricity, Denmark (DK)	KWH	0.308
	*	Electricity, Finland (FI)	KWH	0.187
	*	Electricity, France (FR)	KWH	0.083
	*	Electricity, Germany (DE)	KWH	0.441
	*	Electricity, Greece (GR)	KWH	0.731
	*	Electricity, Hungary (HU)	KWH	0.331
	*	Electricity, Iceland	KWH	0.001
	*	Electricity, Ireland (IE)	KWH	0.486
	*	Electricity, Italy (IT)	KWH	0.398

Table 20. (Continued)

Primary Category - Energy				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Electricity (No transmission loss)	*	Electricity, Luxembourg (LU)	KWH	0.315
	*	Electricity, Netherlands (NL)	KWH	0.392
	*	Electricity, Norway (NO)	KWH	0.005
	*	Electricity, Poland (PL)	KWH	0.653
	*	Electricity, Portugal (PT)	KWH	0.384
	*	Electricity, Slovak Republic (SK)	KWH	0.217
	*	Electricity, Spain (ES)	KWH	0.326
	*	Electricity, Sweden (SE)	KWH	0.04
	*	Electricity, Switzerland (CH)	KWH	0.027
	*	Electricity, Turkey	KWH	0.495
	*	Electricity,United Kingdom (GB)	KWH	0.487
	*	Electricity,European Union, EU-27	KWH	0.351
Gasoline & Petrol	1570	Petrol, unleaded, at refinery/CH U	kg	0.76
	*	Petrol, unleaded, at refinery/CH U (L)	Lkg	3.304

Table 20. (Continued)

Primary Category - Energy				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Gasoline & Petrol	1571	Petrol, unleaded, at refinery/RER U	kg	0.679
	*	Petrol, unleaded, at refinery/RER U (L)	L	3.193
Diesel		Diesel (kg)	kg	0.624
	*	Diesel (L)	L	3.358
	1540	Diesel, at refinery/CH U	kg	0.627
	*	Diesel, at refinery/CH U (L)	L	3.413
	1541	Diesel, at refinery/RER U	kg	0.485
	*	Diesel, at refinery/RER U (L)	L	3.19
Fuel oil		Fuel oil	kg	0.622
	*	Fuel oil (L)	L	3.752
		Heavy fuel oil, at refinery/CH U	kg	0.59
	*	Heavy fuel oil, at refinery/CH U (L)	L	3.719
		Heavy fuel oil, at refinery/RER U	kg	0.427

Table 20. (Continued)

Primary Category - Energy				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Fuel oil	*	Heavy fuel oil, at refinery/RER U (L)	L	3.551
Kerosene	1553	Kerosene, at refinery/CH U	kg	0.627
	*	Kerosene, at refinery/CH U (L)	L	3.343
	1554	Kerosene, at refinery/RER U	kg	0.481
	*	Kerosene, at refinery/RER U (L)	L	3.16
Liquefied Petroleum Gas (LPG)	11798	Liquefied petroleum gas, at service station/CH U	kg	0.704
	*	Liquefied petroleum gas, at service station/CH U (L)	L	2.138
	*	Liquefied petroleum gas, at service station/CH U (L)	L	3.14
Natural Gas (NG)		Natural gas (m3)	m3	0.328
	*	Natural gas (L)	L	3.086
	1412	Natural gas, at long-distance pipeline/CH U	kg	0.365
	*	Natural gas, at long-distance pipeline/CH U (L)	L	2.928
	1413	Natural gas, at long-distance pipeline/RER U	kg	0.38
	*	Natural gas, at long-distance pipeline/RER U (L)	L	2.949

Table 20. (Continued)

Primary Category - Energy				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Coal	11072	Hard coal supply mix, at regional storage/US U	kg	0.169
	*	Hard coal supply mix, at regional storage/US U	kg	2.862
	886	Hard coal supply mix/AT U	kg	0.316
	*	Hard coal supply mix/AT U	kg	3.009
	887	Hard coal supply mix/BE U	kg	0.305
	*	Hard coal supply mix/BE U	kg	2.998
	11094	Hard coal supply mix/CN U	kg	0.974
	*	Hard coal supply mix/CN U	kg	3.667
	895	Hard coal supply mix/CZ U	kg	0.278
	*	Hard coal supply mix/CZ U	kg	2.971
	889	Hard coal supply mix/DE U	kg	0.36
	*	Hard coal supply mix/DE U	kg	3.053
	890	Hard coal supply mix/ES U	kg	0.317

Table 20. (Continued)

Primary Category - Energy				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Coal	*	Hard coal supply mix/ES U	kg	3.01
	891	Hard coal supply mix/FR U	kg	0.276
	*	Hard coal supply mix/FR U	kg	2.969
	896	Hard coal supply mix/HR U	kg	0.316
	*	Hard coal supply mix/HR U	kg	3.009
	892	Hard coal supply mix/IT U	kg	0.264
	*	Hard coal supply mix/IT U	kg	2.957
	893	Hard coal supply mix/NL U	kg	0.265
	*	Hard coal supply mix/NL U	kg	2.958
	897	Hard coal supply mix/PL U	kg	0.28
	*	Hard coal supply mix/PL U	kg	2.973
	894	Hard coal supply mix/PT U	kg	0.2
	*	Hard coal supply mix/PT U	kg	2.893
	898	Hard coal supply mix/SK U	kg	0.324

Table 20. (Continued)

Primary Category - Energy				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Coal	*	Hard coal supply mix/SK U	kg	3.017
Steam		**		
Water	5739	Tap water, at user/CH U	kg	0.000166
	2288	Tap water, at user/RER U	kg	0.000317

Note. *Table 20:* * *is not from Ecoinvent V2.2;* ** *is related data but there is no corresponding information; the data of electricity in Ecoinvent, such as Gasoline & Petrol, Diesel, Fuel oil, Kerosene, Liquefied Petroleum Gas, Natural Gas and Coal are emission factor from refinery. After some conversion, they have become general cases which closer to the current situation.*

Table 21. Transportation related emission factor

Primary Category - Transportation				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Aircraft	1893	Transport, aircraft, freight, Europe/RER U	tkm	1.67
	1894	Transport, aircraft, freight, intercontinental/RER U	tkm	1.07
	1892	Transport, aircraft, freight/RER U	tkm	1.1
Truck, Lorry	10758	Transport, lorry 3.5-7.5t, EURO3/RER U	tkm	0.484
	10759	Transport, lorry 3.5-7.5t, EURO4/RER U	tkm	0.468
	10760	Transport, lorry 3.5-7.5t, EURO5/RER U	tkm	0.473
	7300	Transport, lorry 7.5-16t, EURO3/RER U	tkm	0.238
	7301	Transport, lorry 7.5-16t, EURO4/RER U	tkm	0.221
	7302	Transport, lorry 7.5-16t, EURO5/RER U	tkm	0.224
	7303	Transport, lorry 16-32t, EURO3/RER U	tkm	0.185
	7304	Transport, lorry 16-32t, EURO4/RER U	tkm	0.165
	7305	Transport, lorry 16-32t, EURO5/RER U	tkm	0.168
	7306	Transport, lorry >32t, EURO3/RER U	tkm	0.121

Table 21. (Continued)

Primary Category - Transportation				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Truck, Lorry	7307	Transport, lorry >32t, EURO4/RER U	tkm	0.105
	7308	Transport, lorry >32t, EURO5/RER U	tkm	0.107
	1943	Transport, lorry >16t, fleet average/RER U	tkm	0.133
	1944	Transport, lorry >28t, fleet average/CH U	tkm	0.137
	1942	Transport, lorry 20-28t, fleet average/CH U	tkm	0.194
	1941	Transport, lorry 3.5-16t, fleet average/RER U	tkm	0.257
	1940	Transport, lorry 3.5-20t, fleet average/CH U	tkm	0.279
	188	Transport, tractor and trailer/CH U	tkm	0.309
Ocean		Bulk carrierocean,technology mix, 100.000-200.000 dwt RER S	tkm	0.00243
		Container ship ocean, technology mix, 27.500 dwt pay load capacity RER S	tkm	0.0131
		Transport, ocean freighter, average fuel mix/US	tkm	0.0183

Table 21. (Continued)

Primary Category - Transportation				
Secondary Category	**ID**	**Name in EcoinventV2.2**	**Unit**	**Emission Factor**
Ocean		Transport, ocean freighter, diesel powered/US	tkm	0.0166
		Transport, ocean freighter, residual fuel oil powered/US	tkm	0.0185
Rail	1983	Transport, freight, rail/RER U	tkm	0.0394
	11095	Transport, coal freight, rail/CN U	tkm	0.0443
	11073	Transport, freight, rail, diesel/US U	tkm	0.0497

Note. *Table 21**:** As for oil tank trucks for transportation in CPC Corporation, Taiwan, there are two kinds of oil tank trucks. The first one is an empty truck (about 10 tons weight), and the capacity of the oil for a truck is about 15 to 16 tons, so the weight of a full truck will be 25 to 26 tons. The second one is an empty trailer (about 11 tons weight), and the capacity of the oil for a trailer is about 24 tons, so the weight of a full trailer will be 35 tons.*

5.3.3 Inventory Table for Supply Chain Companies

In the speaking of supply chain companies having done their own inventory analysis on their product, they should fill in the table, as shown in Table 22, to prove the correctness of the result to the primary company as long as they follow the government's regulation and the result is confirmed by the third parties. Apparently, it is a simple table, but it can be used for both B2B and B2C products. Besides, if supply chain companies want to perform the inventory analysis on their product, they can also use the same table to perform their inventory analysis and some detail information can be found from the previous table of different categories of related emission factor. Finally, the result should be confirmed by the third parties in the same way.

Table 22. Inventory table for supply chain companies

Company (Supply)	**Name**	**Location**	**Contact person**	**Tel.**	**E-mail**	**Note**				
Product	**Name**	**Item number**	**Item number (supply)**	**Spec.**	**weight**	**Inventory date**	**Product figure**			**Note**
Process map of product's life cycle										
Material	**Activity**	**Item number**	**Amount usage (activity data)**	**Unit**	**Allocation rule**	**Ingredient**	**Percentage (%)**	**Carbon emissions factor**	**Carbon footprint of a given activity**	**Note**

Table 22. (Continued)

	Activity	Item number	Activity data	Unit	Allocation rule			Carbon emissions factor	Carbon footprint of a given activity	Note
Manufacture										
Transportation	**Activity**	**Transp. tool**	**Distance (km)**	**Weight (ton)**	**Allocation rule**	**Beginning place**	**End place**	**Carbon emissions factor**	**Carbon footprint of a given activity**	**Note**

Table 22. (Continued)

Use	**Activity**		**Activity data**	**Unit**	**Allocation rule**			**Carbon emissions factor**	**Carbon footprint of a given activity**	**Note**
End-of-life	**Activity**	**Item number**	**Activity data**	**Unit**	**Allocation rule**			**Carbon emissions factor**	**Carbon footprint of a given activity**	**Note**
Product carbon footprint										

5.3.4 Summary

In this database, particularly in "Electricity", there are only data for one specific year, and lack of data for different category. Therefore, it needs every supply chain company to do inventory analysis without hesitate and collect other data from different database or public data to update data quality. At last, it will be the standard database in Asia for display industry.

6 Case Study of Standard Calculation Product Carbon Footprint of a TFT LCD Module and Related Final Products (Appendix B)

6.1 Goal and Scope

The goal and scope are defined in the previously content. Just follow the detailed content as mentioned previously to calculate the product carbon footprint. In order to increase the comparability of product carbon footprint of LCD module, it is necessary to select some basic parts and high GHG emission parts in LCD module for establishing LCD module product carbon footprint standard calculation. Besides, the aim is to let supply chain company to have its own ability to calculate carbon footprint of their components by demonstrating this assessment. This example is using bill-of-material (BOM) data of a 32inch TV in 2009 provided by AUO Corp.

6.2 Fundamental Parts of a TFT-LCD Module

It is important to understand the fundamental parts of TFT-LCD module. According to the introduction of TFT-LCD Process and TFT-LCD module, as shown in Table 23, some basic parts and high GHG emission parts are selected to be the necessary parts that must be calculated in the carbon footprint standard of a TFT-LCD module. On the other hand, some supplementary materials (chemicals) are also selected to be the necessary parts such as Nitrous oxide, Sulfur hexafluoride, Nitrogen trifluoride and so on.

Table 23.Name of fundamental parts in both Chinese and English [7]

Chinese	English
前框	Bezel front
偏光片	Polarizer film
彩色濾光片	Color filter
液晶	Liquid crystal
TFT 玻璃	TFT array glass
驅動 IC 與印刷電路板	Driver IC & PCBA
擴散片	Diffuser film
擴散板	Diffuser plate
膠框	Plastic frame
背光源	Light source
背板	Bezel back
主控制版	Control board
背光模組點燈器	Inverter

6.3 System Boundaries of a TFT-LCD Module and a TV set

As mentioned before, the standard calculations are classified into two types of standards, primary company and supply chain company, respectively. Primary company is the midstream company that manufacture TFT-LCD module. As for typically primary companies, they will manufacture the array (+color filter) and cell in the same facility and module assembly will be execute in another facility, as shown in Figure 4. Finally, they will offer LCD modules for the downstream companies such as TV set manufacturers, and the system boundaries will be extended, as shown in No.3 in Table 24.

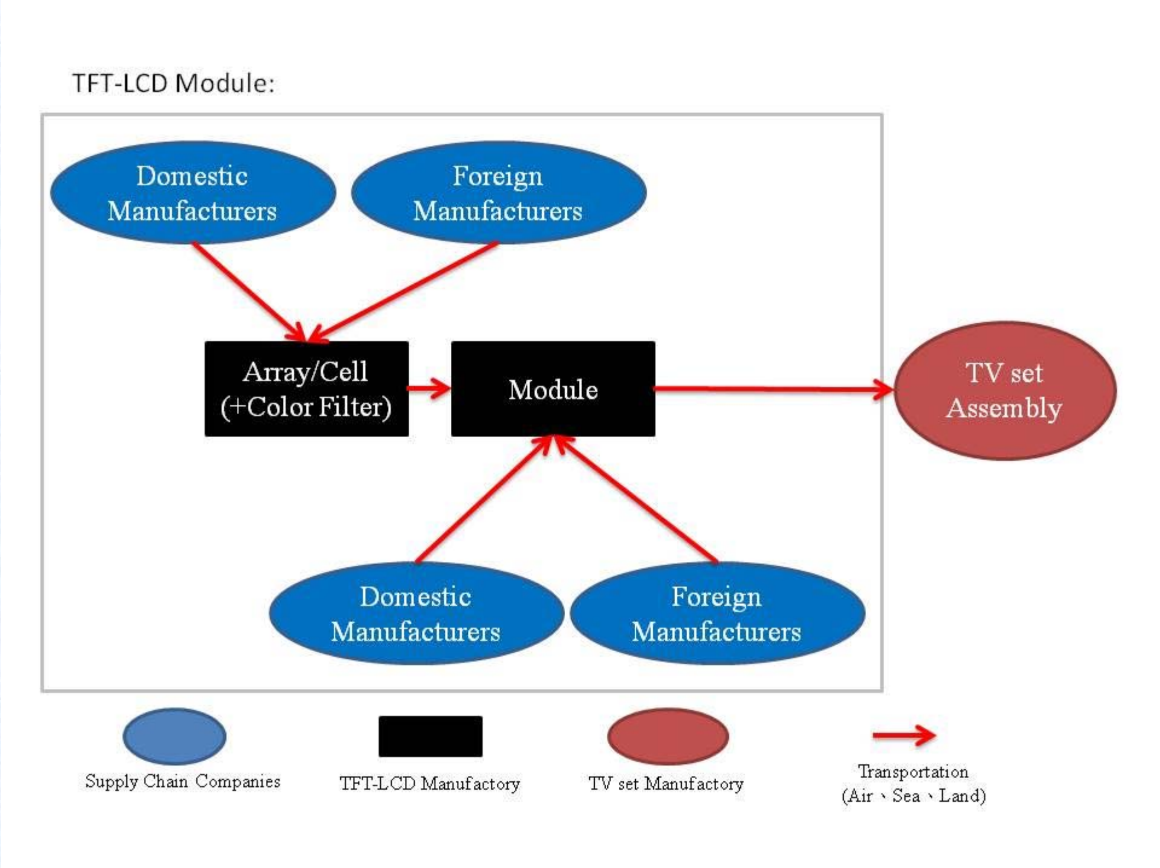
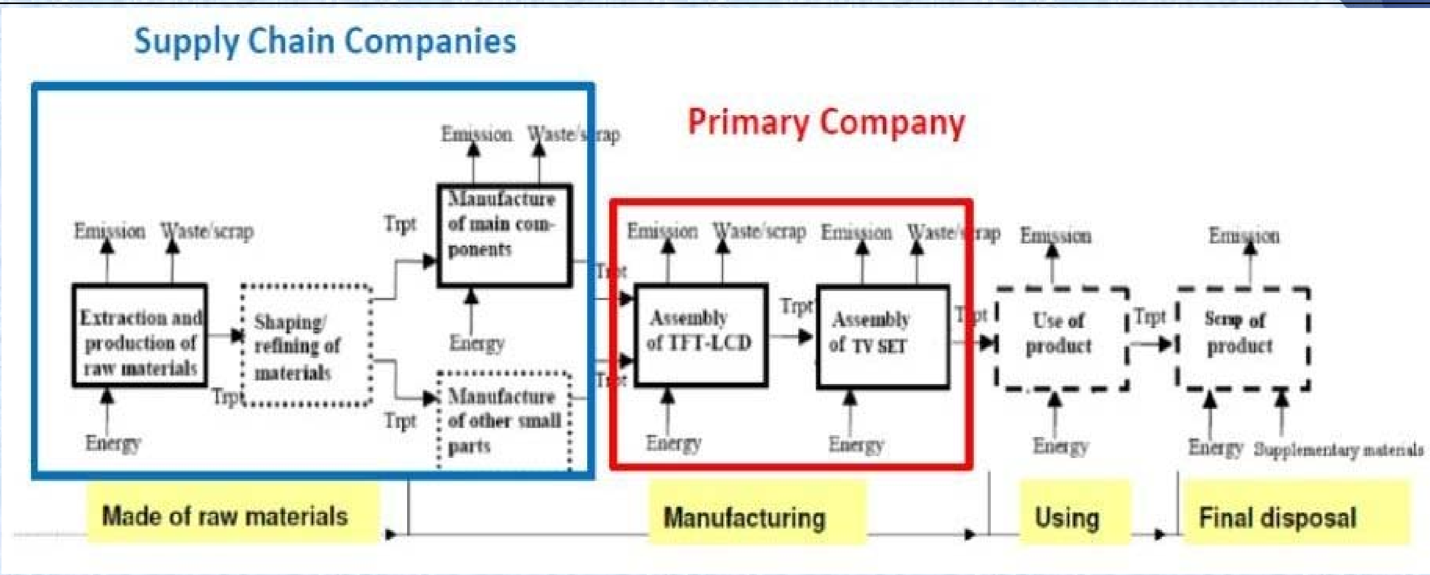


Figure 4. System boundary of the primary company for display industry

Table 24. System boundary of a final product (TV set) [8]

<table>
<tr><th>No.</th><th>Different boundary conditions</th></tr>
<tr><td>1.</td><td>
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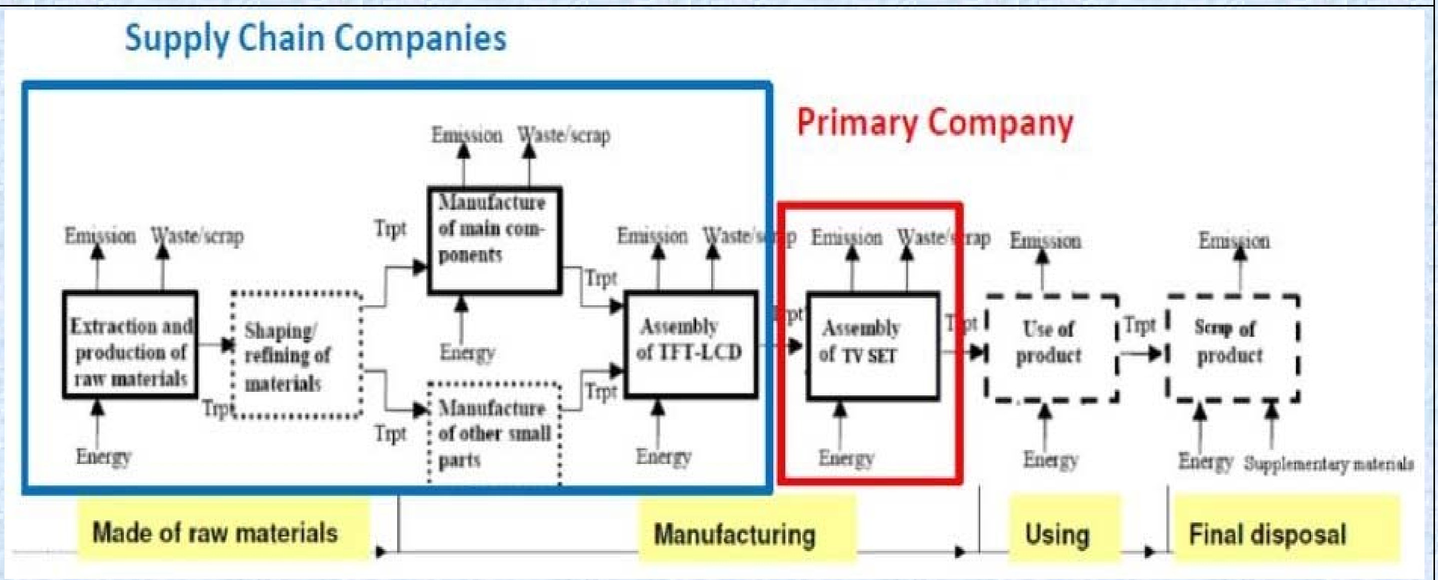
<tr><td>2.</td><td>
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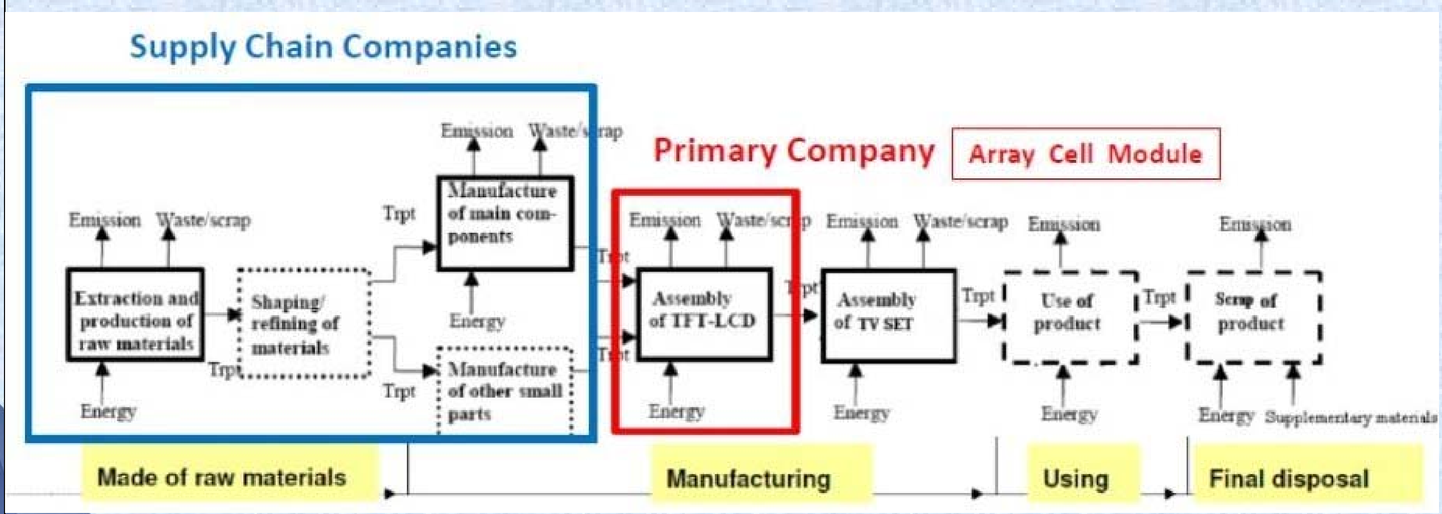
<tr><td>3.</td><td>
</td></tr>
</table>

6.4 TFT-LCD Module Calculation (B2B)

For calculation product carbon footprint of a LCD module, the following equations should be used [2]:

MCF_{LCDM} (kg CO_2 eq) = [(GHG_F/A_{input}) x ($A_{LCDM}+A_{scrap}$)]

where

MCF_{LCDM} = the manufacturing carbon footprint of a single LCD module (kg CO_2 eq)

GHG_F = the total manufacturing facility greenhouse gas emission in a year (kgCO_2 eq)

A_{input} = the total input glass area (for TFT and color filter) brought into the facility in a year (in m^2)

A_{scrap} = the area of glass scrap (will be a function of the generation and display area)

Note: *scrap may not be relevant for module assembly*

A_{LCDM} = the total area of a specific LCD (in m^2)

PCF of a LCD Module = $MCF_{LCDM}+UCF_{LCDM}$

UCF_{LCDM} (kg CO_2 eq) = ($CF_e x W_e$) +($CF_b x W_b$)+($CF_h x W_h$)+... and some other components

where

UCF_{LCDM} = the upstream carbon footprint of a single LCD module (kg CO2 eq)

CF_e = average carbon footprint of electronics per kg of electronics from LCI database (kg CO_2 eq/kg electronics)

W_e = total weight of the electronics within the LCD Module

CF_b = average carbon footprint of backlight unit per kg of electronics from LCI database (kg CO_2 eq/kg backlight unit)

W_b = total weight of the backlight unit within the LCD Module

CF_h = average carbon footprint of housing per kg of electronics from LCI database (kg CO_2 eq/kg housing)

W_h = total weight of the housing within the LCD Module

Note. *If supply chain companies can offer the inventory data of their components, the data source doesn't have to be LCI database.*

The foregoing is the standard calculation procedure for a TFT-LCD module in manufacturing stage. The whole coverage (B2B) of a TFT-LCD module will be present in the following contents by using a 32inch TV.

6.4.1 TFT-LCD Module - Raw Materials Stage

According to BOM of a 32inch module, the following chosen parts are some necessary parts and high GHG emission chemicals for the standard calculation as shown in Table 25 and Table 26. Furthermore, there are special gases which have extremely high emissions factor. As a result, there some assumptions for recycling those gases, as shown in Table 27 and Table 28. At last, the carbon footprint of the TFT-LCD module for raw material stage is 405.292552 kg CO_2 eq, as shown in Table 38.

Table 25. Carbon footprint of the TFT-LCD module (Raw material stage – Array, Cell, CF, EE, OM and so on)

	Category		Parts Names	kg	Emission Factor (kgCO_2eq/kg)	Production (kgCO2eq)
Module	Panel	EE	PCBA_A	0.018	222.78	4.01004
			PCBA_B	0.028	228.57	6.39996
			Driver IC_A	0.000179	1990.63	0.356999584
			Driver IC_B	0.000824	897.69	0.740001775
			ACF	0.000645	60.14	0.038799983
		OM	Bezel front	0.582	4.16	2.42112
			Tape	0.004	7.65	0.0306
			Cushion bezel poron_A	0.008	84.25	0.674
			Cushion bezel poron_B	0.008	170	1.36
			Thermal pad	0.0084	5.13	0.043092
			Plate shielding	0.021	38.62	0.81102
			Screw_A	0.007765	0.02	0.000155304
			Screw_B	0.00453	3.18	0.014404446
			Backlight unit	Lack of data	Lack of data	Lack of data

Table 25. (Continued)

Module	Category		Parts Names	kg	Emission Factor (kgCO_2eq/kg)	Production (kgCO2eq)
Module	Panel	OM	Inverter	0.16	300.63	48.1008
			Plate diffuser	0.6	10.85	6.51
			Sheet diffuser	0.077	2.71	0.20867
			Sheet DBEF	0.14	2.59	0.3626
			Sheet prism	0.29	7.34	2.1286
			Sheet reflector	0.06	11	0.66
			Bezel back	2.7	3.63	9.801
			Frame lower	0.091	9.45	0.85995
			Fame upper	0.085	9.59	0.81515
			Inverter cover	0.09	11.67	1.0503
			Lamp support	0.0056	14.66	0.082096
			Lamp block (right)	0.136	8.75	1.19
			Lamp block (left)	0.136	8.75	1.19
			Tape	0.0022	2.55	0.00561
			Label	0.00043	14.7	0.006321
			Rubber_A	0.0032	20.38	0.065216
			Rubber_B	0.00011	Lack of data	Lack of data
			Rubber_C	0.00011	Lack of data	Lack of data
			Screw_C	0.0024	88.75	0.213

Table 25. (Continued)

	Category		Parts Names	kg	Emission Factor (kgCO$_2$eq/kg)	Production (kgCO2eq)
Module	Panel	OM	Screw_D	0.003	5.2	0.0156
			Connector	0.000738	172.09	0.12700242
			Cable_A	0.0002	332	0.0664
			Cable_B	0.0002	332.5	0.0665
			CCFL	0.080412	717.55	57.6996306
			Rubber_D	0.0082	1.8	0.01476
		Array	Target ITO	0.0045	119.11	0.535995
			Mo target	0.0184	10.16	0.186944
			Al target	0.04	2.53	0.1012
			Glass	0.3	4.4	1.32
		Cell	AU ball	6.4E-06	6687.5	0.0428
			Sealant	0.000123	5.31	0.000653427
			Power seal	1.33E-06	2.7	3.59937E-06
			Polarizer_A	0.112	55.89	6.25968
			Polarizer_B	0.115	53.39	6.13985
			Liquid polyimides	0.006	22.67	0.13602
			Liquid crystal	0.001046	2.02	0.002112872
		Color filter	Glass	0.3	4.4	1.32
			ITO_A	0.0132	85.61	1.130052

Table 25. (Continued)

	Category		Parts Names	kg	Emission Factor (kgCO$_2$eq/kg)	Production (kgCO2eq)
Module	Panel	Color filter	ITO_B	0.01782	0.25	0.004455
			BM	0.04244	2.17	0.092094583
			MVA	0.038419	5.05	0.19401595
			Color resist	0.172082	3.03	0.521407854
			PS	0.068488	0.66	0.045202212
		Package	Label	0.00047	13.4	0.006298
			Film protect	0.00032	2.75	0.00088
			Crepe paper tape	0.0012	1.24	0.001488
			Bag anti-static	0.05	2.14	0.107
			Cushion packing	0.6125	0.31	0.189875
			Packing carton	0.4125	0.32	0.132
			Label	0.000035	0.38	0.0000133
			OPP	0.0006	Lack of data	Lack of data

Table 26. Carbon footprint of the TFT-LCD module (Raw material stage - Supplementary material)

	Category	Parts Names	kg	Emission Factor (kgCO_2eq/kg)	Production (kgCO2eq)
Module	Supplementary material	Aluminum etch	2.282205	1.6	3.65152764
		EBR	2.003199	2.05	4.106557269
		Developer	0.91059	0.06	0.054635412
		Stripper	19.96597	2.61	52.11117588
		Photo resist	0.925298	1.36	1.258404676
		NMP	0.213057	Lack of data	Lack of data
		Oxalic acid	0.202835	Lack of data	Lack of data
		Isopropyl alcohol	0.017583	3.19	0.05608865
		Oxygen	1.963	0.41	0.804829889
		Argon	0.087231	0.31	0.027041733
		Hydrogen	2.263108	1.66	3.756759318
		Helium gas	0.193409	0.93	0.179870499
		Ammonia	0.147946	2.12	0.313645378
		Chlorine	0.077815	0.88	0.068477291
		Ethanol	0.083134	0.33	0.02743411
		Acetone	0.152393	2.22	0.338312427
		PH_3/H_2	0.062564	1.66	0.103856736
		Photo resist	1.119983	3.25	3.639944406
		Thinner	0.884349	3.55	3.139439234

Table 26. (Continued)

Module	Category	Parts Names	kg	Emission Factor (kgCO$_2$eq/kg)	Production (kgCO2eq)
Module	Supplementary material	Eterpol EPLL301	0.006707	11.54	0.077401469
		PK-LCG432	0.088461	Lack of data	Lack of data
		Soda buffer solution	1.698829	1.22	2.072571651
		Hydrogen peroxide	0.000252	1.21	0.000305072
		Sodium bisulfite	0.002088	Lack of data	Lack of data
		Sodium hypochlorite	5.01E-05	0.92	4.60806E-05
		Sodium hydroxide	0.028642	1.24	0.035516575
		Sulfuric acid	0.026368	0.14	0.003691526
		Polymer	0.000365	Lack of data	Lack of data
		Poly aluminum chloride (PAC)	0.02249	Lack of data	Lack of data
		Calcium chloride	0.024142	0.89	0.021486371
		Hydrogen peroxide	0.000257	1.21	0.000311407
		Sodium bisulfite	0.002132	Lack of data	Lack of data
		Sodium hypochlorite	5.11E-05	0.92	4.70374E-05
		Sodium hydroxide	0.029237	1.24	0.036253988
		Sulfuric acid	0.026916	0.14	0.003768171
		Polymer	0	Lack of data	0
		Poly aluminum chloride (PAC)	0	Lack of data	0
		Calcium chloride	0.024643	0.89	0.021932482
SUM					242.5207723

Note. *If supply chain companies have done their inventory analysis, the data can be used primarily for calculation. If supply chain companies didn't do the inventory analysis, then the standard database for display industry can be used, as shown in Appendix A.*

Table 27. Carbon footprint of the TFT-LCD module (Raw material stage – Special gases of supplementary material)

Special Gases	kg	Recycle Ratio (%)	Actual Usage (kg)	Emission Factor (kgCO2eq/kg)	Production (kgCO2eq)
Nitrous oxide (N_2O)	32.39178173	99.83690249	0.052830189	265	14
Carbon dioxide (CO_2)	2.083526356	16.00778197	1.75	1	1.75
Nitrous oxide (N_2O)	0.044445447	100	0	265	0
SUM					15.75

Note. *For Table 27, there are different process that requires nitrous oxide (N_2O) and actual recycling situation for different process is different. Hence, there are two nitrous oxide (N_2O) in this table for two different consumptions and assume all special gases are only used once in the module in the raw material stage in this calculation.*

As mentioned previously in the standard estimation of carbon footprint emissions for those powerful greenhouse gases, the estimation results of special gases are shown in **Table 28**.

Table 28. Carbon emissions of the TFT-LCD module (Raw material stage – FCs of supplementary material)

	Input (kg)	Actual use ratio (%)	Emissions Factor (kgCO2eq/kg)	Production emission (kgCO2eq)
Nitrogen trifluoride (NF_3)	0.218747807	2.61	16100	91.92001598
Sulfur hexafluoride (SF_6)	0.0685601	3.42	23500	55.10176375
SUM				147.0217797

6.4.2 TFT-LCD Module - Manufacturing Stage

Because of lacking detailed data about where to manufacture this TFT-LCD module, there are some data from other literature will be used, as shown in Table 29. However, the data of total greenhouse emissions for this manufactory only includes Scope1 and Scope2 emissions and greenhouse emissions for manufactory of module assembly is not included because scope 3 emissions is hard to calculate and emission hotspots for manufacturing stage are array (+color filter) and cell processes. Therefore, it is acceptable for demonstration for this case study in manufacturing stage.

The scenario is this 32inch TFT-LCD module shipping for the final product (a 32inch TV set). According to the generations of the module manufactories, above 30inch modules should be manufactured in 6th or even higher generation manufactories. In this stage, we assume that this module is manufactured in 6th generation (G6) manufactory, which located in Taichung, Taiwan, and this G6 manufactory only manufactures standard glass substrates for 32inch modules and the related processes for this manufactory only includes array(+color filter) and cell processes, as shown in Table 30. According to the maximum cutting numbers for a standard size glass substrate, there are eight 32inch modules can be cut from a standard size glass substrate, and the remaining area for a standard size glass substrate will be 0.52 m^2, as shown in Table 30. Consequently, using the following information for standard calculation for manufacturing stage will the carbon footprint result of manufacturing a 32inch module in this G6 manufactory, as shown in Table 32.

Table 29. Related data for calculation from other literature [9]

Generation of Manufactory	Total Green House Gas Emissions for This Manufactory in 2009 (kg CO_2eq)	Total Input Glass Area for This Manufacturing Process in 2009 (m^2)
G6 manufactory	780781000	5443934

Table 30. Standard size for a glass substrate in the G6 manufactory [9]

G6 manufactory	Length(mm) x Width(mm)	Area(m^2)
Standard size for a glass substrate	1500x1850	2.775

Table 31. Size for a 32inch module and remaining area

Generation Manufactory	Size for a Standard Glass Substrate	Maximum Cutting Numbers for 32inch Modules from a Standard Size Glass Substrate	Size for a 32inch Module	Remaining Area (Scrap Area)
G6 manufactory	1500mm x 1850mm	8 modules	708.42mm x 398.48 mm ($0.28m^2$)	0.52 m^2

Table 32. Carbon footprint of the TFT-LCD module (Manufacturing stage)

Standard Calculation	Carbon Footprint for the TFT-LCD Module (A 32inch Module) for manufacturing stage
(780781000/5443934) *(0.28+0.52)	114.6315034 $kgCO_2eq$

6.4.3 TFT-LCD Module - Transportation Stage

In typically primary companies, the array (+color filter) and cell process will be put in the same manufactory and module process will be moved to another manufactory. The reason is that the array (+color filter) and cell process are technology-intensive processes and module process is labor-intensive process. Therefore, it will be easier to control the pollutants and waste in the same manufactory which has a technology-intensive process and choosing countries which have low labor cost to reduce the cost of the product for module process is necessary task for every primary company.

In the manufacturing stage, we have already assumed that the array (+color filter) and cell processes are in G6 manufactory which located in Taichung, Taiwan. In order to reduce the labor cost for module process, we assume that manufactory which has module process is located in Xiamen, China. In this stage, the calculation of carbon footprint should follow the real purchase status of primary company. However, the real purchase status from different supply chain companies is not given. The following companies randomly chosen from real companies around the world, as shown in Table 33, are used for demonstration of calculation of carbon footprint in transportation stage.

In transportation stage, there are only some parts of components and chemicals are chosen to be calculate for carbon footprint emissions because the amount of some components is extremely small and the allocation method for calculation uses the ration between the weight of specific material and the maximum load of each transportation to allocate carbon footprint emissions.

Table 33. Some important purchase status (Randomly choose from real companies around the world)

Process and Chemicals	Parts	Name of Supply Chain Company
Array	Glass	Corning Inc. Taiwan
Cell	Polarizer_A	Sumika Technology Co., Ltd.
	Polarizer_B	Sumika Technology Co., Ltd.
Color filter	Glass	Corning Inc. Taiwan
	Color resist	Topgiga Material CORP.
OM	Bezel front	I-CHIUN PRECISION
	Inverter	Darfon Electronics Corp.
	Plate diffuser	Darwin Precisions Corp. (Xiamen)
	Sheet diffuser	Darwin Precisions Corp. (Xiamen)
	Sheet DBEF	3M Taiwan Ltd.
	Sheet prism	3M Taiwan Ltd.
	Bezel back	I-CHIUN PRECISION INDUSTRY CO., LTD.
	Frame lower	I-CHIUN PRECISION INDUSTRY CO., LTD.
	Fame upper	I-CHIUN PRECISION INDUSTRY CO., LTD.
	Inverter cover	Darwin Precisions Corp. (Xiamen)
	Lamp block (right)	Lextar Electronics Corporation.

Table 33. (Continued)

Process and Chemicals	Parts	Name of Supply Chain Company
OM	Lamp block (left)	Lextar Electronics Corporation.
	CCFL	Lextar Electronics Corporation.
Package	Cushion packing	SEN WEI PACKING CO., LTD.
	Packing carton	Chun Ying Paper CO., LTD.
Supplementary material	Aluminum etch	TAIWAN MAXWAVE CO., LTD.
	EBR	SUN SURFACE TECHNOLOGY CO., LTD.
	Developer	SUN SURFACE TECHNOLOGY CO., LTD.
	Stripper	SUN SURFACE TECHNOLOGY CO., LTD.
	Nitrogen trifluoride	Jing He Science Co., LTD.
	Photo resist_A	S.M.S. Technology CO., LTD.
	NMP	ECHO CHEMICAL CO., LTD.
	Oxalic acid	First Chemical Co., Ltd.
	Nitrous oxide	Jing He Science Co., LTD.
	Oxygen	Jing He Science Co., LTD.
	Argon	Jing He Science Co., LTD.
	Carbon dioxide	Jing He Science Co., LTD.
	Hydrogen	Jing He Science Co., LTD.
	Helium gas	Jing He Science Co., LTD.
	Ammonia	Jing He Science Co., LTD.

Table 33. (Continued)

Process and Chemicals	Parts	Name of Supply Chain Company
Supplementary material	Chlorine	Cheng Chiao Group., LTD.
	Ethanol	ECHO CHEMICAL CO., LTD.
	Acetone	ITOCHU Taiwan Corp.
	Photo resist_B	S.M.S. Technology CO., LTD.
	Thinner	SUN SURFACE TECHNOLOGY CO., LTD.
	PK-LCG432	Lack of data
	Soda buffer solution	Lack of data

Note. *These supply chain companies are chosen to be in this calculation for only demonstration, so there is a chance that those companies do not have that exact the same materials or chemicals. As a result, the intention is to show the fact of complexity in choosing different material or chemical from different supply chain companies*

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According to the selected supply chain companies, each material will be delivered to the corresponding manufactories. Besides, we assume that the land transportation in Taiwan will be a lorry (3.5t) which can carry 1.5 tons materials; the land transportation in China is the same as Taiwan; the sea transportation between different countries will be a freight ship which can carries 20TEU (7188.48 tons) materials, as shown in Table 34. (***Note.*** *1TEU can carries 28080kg of material* [10]).

Table 34. Information of transportation mode and corresponding emission factor

Information of Transportation Mode	Maximum Load	Emission Factor (kgCO_2eq/tkm)	Data Source
Land Transportation in Taiwan (Lorry, 3.5t)	1.5t	0.24 [11]	Carbon Footprint Calculation Platform, Taiwan
Sea Transportation between Different Countries (Standard Freight Ship)	20TEU (7188.48t)	0.010751	Ecoinvent V 2.2 – ID:1968, transport, transoceanic freight ship, OCE
Land Transportation in China (Lorry, 3.5t)	1.5t	0.24	Lack of data replaces it by data in Taiwan

Google Maps is used to plan the shortest way between supply chain companies and the primary company and measure the real distance for land transportation in Taiwan, and China. On the other hand, we assume that there are two ports. One is Taichung Port (Taiwan) and the other one is Xiamen Port (China) The real distance between two ports is fixed value (136 nautical mile) in sea transportation (***Note.*** *1 nautical mile = 1.852 meters*). The following information is the transport planning between supply chain companies and primary companies, as shown in Table 35.

In this result, we assume that each transportation mode is independent, and we do not consider the volume of material. It means that each transportation can carry the maximum weight of material same as its maximum load. For the carbon footprint of each material, it will be the sum of allocation result of each independent transportation mode. Besides, the method of allocation is about the ratio of the weight of corresponding material to the maximum carrying load of corresponding material, as shown in Table 36. Finally, the carbon footprint of transportation stage is 1.573435201 kgCO_2eq, as shown in Table 37.

Table 35. Result of transport planning between supply chain companies and primary companies (LT: Land Transportation, ST: Sea Transportation)

Process and Chemicals	Parts	Location of Supply Chain Company	Location of Primary Company	Result of transport planning		
				LT(Taiwan) km	ST(Countries) km	LT(China) km
Array	Glass	Tainan, Taiwan	Taichung, Taiwan	160	0	0
Cell	Polarizer_A	Tainan, Taiwan	Taichung, Taiwan	160	0	0
	Polarizer_B	Tainan, Taiwan	Taichung, Taiwan	160	0	0
Color filter	Glass	Tainan, Taiwan	Taichung, Taiwan	160	0	0
	Color resist	Miaoli, Taiwan	Taichung, Taiwan	70	0	0
OM	Bezel front	Xinbei, Taiwan	Xiamen, China	150	251.872	35
	Inverter	Taoyuan, Taiwan	Xiamen, China	140	251.872	35
	Plate diffuser	Xiamen, China	Xiamen, China	0	0	(Location too close)
	Sheet diffuser	Xiamen, China	Xiamen, China	0	0	(Location too close)
	Sheet DBEF	Tainan, Taiwan	Xiamen, China	160	251.872	35
	Sheet prism	Tainan, Taiwan	Xiamen, China	160	251.872	35
	Bezel back	Xinbei, Taiwan	Xiamen, China	150	251.872	35

Table 35. (Continued)

Process and Chemicals	Parts	Location of Supply Chain Company	Location of Primary Company	Result of transport planning		
				LT(Taiwan) km	LT(Taiwan) km	LT(Taiwan) km
OM	Frame lower	Xinbei, Taiwan	Xiamen, China	150	251.872	35
	Fame upper	Xinbei, Taiwan	Xiamen, China	150	251.872	35
	Inverter cover	Taoyuan, Taiwan	Xiamen, China	140	251.872	35
	Lamp block (right)	Hsinchu, Taiwan	Xiamen, China	90	251.872	35
	Lamp block (left)	Hsinchu, Taiwan	Xiamen, China	90	251.872	35
	CCFL	Hsinchu, Taiwan	Xiamen, China	90	251.872	35
Package	Cushion packing	Taichung, Taiwan	Taichung, Taiwan	(Location to close)	0	0
	Packing carton	Changhua, Taiwan	Taichung, Taiwan	30	0	0
Supplementary materials	Aluminum etch	Taipei, Taiwan	Taichung, Taiwan	170	0	0
	EBR	Yunlin, Taiwan	Taichung, Taiwan	75	0	0
	Developer	Yunlin, Taiwan	Taichung, Taiwan	75	0	0
	Stripper	Yunlin, Taiwan	Taichung, Taiwan	75	0	0

Table 35. (Continued)

Process and Chemicals	Parts	Location of Supply Chain Company	Location of Primary Company	Result of transport planning		
				LT(Taiwan) km	LT(Taiwan) km	LT(Taiwan) km
Supplementary materials	Nitrogen trifluoride	Jhongli, Taiwan	Taichung, Taiwan	120	0	0
	Photo resist	Taipei, Taiwan	Taichung, Taiwan	170	0	0
	NMP	Taichung, Taiwan	Taichung, Taiwan	(Location to close)	0	0
	Oxalic acid	Taipei, Taiwan	Taichung, Taiwan	170	0	0
	Nitrous oxide	Jhongli, Taiwan	Taichung, Taiwan	120	0	0
	Oxygen	Yunlin, Taiwan	Taichung, Taiwan	75	0	0
	Argon	Yunlin, Taiwan	Taichung, Taiwan	75	0	0
	Carbon dioxide	Yunlin, Taiwan	Taichung, Taiwan	75	0	0
	Hydrogen	Yunlin, Taiwan	Taichung, Taiwan	75	0	0
	Helium gas	Yunlin, Taiwan	Taichung, Taiwan	75	0	0
	Nitrous oxide	Jhongli, Taiwan	Taichung, Taiwan	120	0	0
	Ammonia	Yunlin, Taiwan	Taichung, Taiwan	75	0	0
	Chlorine	Changhua, Taiwan	Taichung, Taiwan	30	0	0

Table 35. (Continued)

Process and Chemicals	**Parts**	**Location of Supply Chain Company**	**Location of Primary Company**	**Result of transport planning**		
				LT(Taiwan) km	LT(Taiwan) km	LT(Taiwan) km
Supplementary materials	Ethanol	Taichung, Taiwan	Taichung, Taiwan	(Location to close)	0	0
	Acetone	Taipei, Taiwan	Taichung, Taiwan	170	0	0
	Photo resist	Taipei, Taiwan	Taichung, Taiwan	170	0	0
	Thinner	Yunlin, Taiwan	Taichung, Taiwan	75	0	0
	PK-LCG432	No exact data (Maybe from Japan)	Taichung, Taiwan	Lack of data	Lack of data	Lack of data
	Soda buffer solution	No exact data (Other country)	Taichung, Taiwan	Lack of data	Lack of data	Lack of data

Table 36. The allocation ratio of each independent transportation mode (LT: Land Transportation, ST: Sea Transportation)

Parts	Usage rate per unit of production (kg)	Maximum Load: LT Taiwan (t)	Maximum Load: ST Countries (t)	Maximum Load: LT China (t)	Allocation Ratio: LT Taiwan	Allocation Ratio: ST Countries	Allocation Ratio: LT China
Glass	0.3	1.5	7188.48	1.5	0.0002	4.17334E-08	0.0002
Polarizer_A	0.112	1.5	7188.48	1.5	7.4667E-05	1.55805E-08	7.46667E-05
Polarizer_B	0.115	1.5	7188.48	1.5	7.6667E-05	1.59978E-08	7.66667E-05
Glass	0.3	1.5	7188.48	1.5	0.0002	4.17334E-08	0.0002
Color resist	0.17208	1.5	7188.48	1.5	0.00011472	2.39386E-08	0.000114721
Bezel front	0.582	1.5	7188.48	1.5	0.000388	8.09629E-08	0.000388
Inverter	0.16	1.5	7188.48	1.5	0.00010667	2.22578E-08	0.000106667
Plate diffuser	0.6	1.5	7188.48	1.5	0.0004	8.34669E-08	0.0004
Sheet diffuser	0.077	1.5	7188.48	1.5	5.1333E-05	1.07116E-08	5.13333E-05

Table 36. (Continued)

Parts	Usage rate per unit of production (kg)	Maximum Load: LT Taiwan (t)	Maximum Load: ST Countries (t)	Maximum Load: LT China (t)	Allocation Ratio: LT Taiwan	Allocation Ratio: ST Countries	Allocation Ratio: LT China
Sheet DBEF	0.14	1.5	7188.48	1.5	9.3333E-05	1.94756E-08	9.33333E-05
Sheet prism	0.29	1.5	7188.48	1.5	0.00019333	4.03423E-08	0.000193333
Bezel back	2.7	1.5	7188.48	1.5	0.0018	3.75601E-07	0.0018
Frame lower	0.091	1.5	7188.48	1.5	6.0667E-05	1.26591E-08	6.06667E-05
Fame upper	0.085	1.5	7188.48	1.5	5.6667E-05	1.18245E-08	5.66667E-05
Inverter cover	0.09	1.5	7188.48	1.5	0.00006	1.252E-08	0.00006
Lamp block (right)	0.136	1.5	7188.48	1.5	9.0667E-05	1.89192E-08	9.06667E-05
Lamp block (left)	0.136	1.5	7188.48	1.5	9.0667E-05	1.89192E-08	9.06667E-05
CCFL	0.08041	1.5	7188.48	1.5	5.3608E-05	1.11862E-08	0.000053608
Cushion packing	0.6125	1.5	7188.48	1.5	0.00040833	8.52058E-08	0.000408333

Table 36. (Continued)

Parts	Usage rate per unit of production (kg)	Maximum Load: LT Taiwan (t)	Maximum Load: ST Countries (t)	Maximum Load: LT China (t)	Allocation Ratio: LT Taiwan	Allocation Ratio: ST Countries	Allocation Ratio: LT China
Packing carton	0.4125	1.5	7188.48	1.5	0.000275	5.73835E-08	0.000275
Aluminum etch	2.2822	1.5	7188.48	1.5	0.00152147	3.17481E-07	0.00152147
EBR	2.0032	1.5	7188.48	1.5	0.00133547	2.78668E-07	0.001335466
Developer	0.91059	1.5	7188.48	1.5	0.00060706	1.26674E-07	0.00060706
Stripper	19.966	1.5	7188.48	1.5	0.01331065	2.7775E-06	0.013310645
Nitrogen trifluoride	0.21875	1.5	7188.48	1.5	0.00014583	3.04303E-08	0.000145832
Photo resist	0.9253	1.5	7188.48	1.5	0.00061687	1.2872E-07	0.000616865
NMP	0.21306	1.5	7188.48	1.5	0.00014204	2.96387E-08	0.000142038
Oxalic acid	0.20283	1.5	7188.48	1.5	0.00013522	2.82166E-08	0.000135223
Nitrous oxide	32.3918	1.5	7188.48	1.5	0.02159452	4.50607E-06	0.021594521
Oxygen	1.963	1.5	7188.48	1.5	0.00130867	2.73076E-07	0.001308666

Table 36. (Continued)

Parts	Usage rate per unit of production (kg)	Maximum Load: LT Taiwan (t)	Maximum Load: ST Countries (t)	Maximum Load: LT China (t)	Allocation Ratio: LT Taiwan	Allocation Ratio: ST Countries	Allocation Ratio: LT China
Argon	0.08723	1.5	7188.48	1.5	5.8154E-05	1.21349E-08	5.81543E-05
Carbon dioxide	2.08353	1.5	7188.48	1.5	0.00138902	2.89842E-07	0.001389018
Hydrogen	2.26311	1.5	7188.48	1.5	0.00150874	3.14824E-07	0.001508739
Helium gas	0.19341	1.5	7188.48	1.5	0.00012894	2.69054E-08	0.000128939
Nitrous oxide	0.04445	1.5	7188.48	1.5	2.963E-05	6.18287E-09	2.96303E-05
Ammonia	0.14795	1.5	7188.48	1.5	9.8631E-05	2.0581E-08	9.86306E-05
Chlorine	0.07782	1.5	7188.48	1.5	5.1877E-05	1.0825E-08	5.18767E-05
Ethanol	0.08313	1.5	7188.48	1.5	5.5422E-05	1.15648E-08	5.54224E-05
Acetone	0.15239	1.5	7188.48	1.5	0.0001016	2.11996E-08	0.000101595
Photo Resist	1.11998	1.5	7188.48	1.5	0.00074666	1.55802E-07	0.000746655
Thinner	0.88435	1.5	7188.48	1.5	0.00058957	1.23023E-07	0.000589566
PK-LCG432	0.08846	1.5	7188.48	1.5	5.8974E-05	1.2306E-08	5.89743E-05
Soda buffer solution	1.69883	1.5	7188.48	1.5	0.00113255	2.36327E-07	0.001132553

Table 37. Carbon footprint of the TFT-LCD module (Transportation stage) (LT: Land Transportation, ST: Sea Transportation)

Parts	LT: Taiwan (tkm)	ST: Countries (tkm)	LT: China (tkm)	Carbon Footprint Emissions ($kgCO_2eq$)
Glass	240	0	0	0.01152
Polarizer_A	240	0	0	0.0043008
Polarizer_B	240	0	0	0.004416
Glass	240	0	0	0.01152
Color resist	105	0	0	0.002890974
Bezel front	225	1810576.835	52.5	0.027416784
Inverter	210	1810576.835	52.5	0.00715326
Plate diffuser	(Location to close)	(Location to close)	(Location to close)	(Location to close)
Sheet diffuser	(Location to close)	(Location to close)	(Location to close)	(Location to close)
Sheet DBEF	240	1810576.835	52.5	0.006931103
Sheet prism	240	1810576.835	52.5	0.014357284
Bezel back	225	1810576.835	52.5	0.127191265
Frame lower	225	1810576.835	52.5	0.004286817
Fame upper	225	1810576.835	52.5	0.004004169
Inverter cover	210	1810576.835	52.5	0.004023709
Lamp block (right)	135	1810576.835	52.5	0.004448271
Lamp block (left)	135	1810576.835	52.5	0.004448271
CCFL	135	1810576.835	52.5	0.002630106

Table 37. (Continued)

Parts	LT: Taiwan (tkm)	ST: Countries (tkm)	LT: China (tkm)	Carbon Footprint Emissions ($kgCO_2eq$)
Cushion packing	(Location to close)	(Location to close)	(Location to close)	(Location to close)
Packing carton	45	0	0	0.00297
Aluminum etch	255	0	0	0.093113955
EBR	112.5	0	0	0.036057576
Developer	112.5	0	0	0.016390624
Stripper	112.5	0	0	0.35938742
Nitrogen trifluoride	112.5	0	0	0.003937461
Photo resist	255	0	0	0.03775214
NMP	(Location to close)	(Location to close)	(Location to close)	(Location to close)
Oxalic acid	255	0	0	0.008275655
Nitrous oxide	112.5	0	0	0.583052071
Oxygen	112.5	0	0	0.035333995
Argon	112.5	0	0	0.001570165
Carbon dioxide	112.5	0	0	0.037503474
Hydrogen	112.5	0	0	0.040735944
Helium gas	112.5	0	0	0.003481365
Nitrous oxide	180	0	0	0.001280029
Ammonia	112.5	0	0	0.002663027
Chlorine	45	0	0	0.000560269

Table 37. (Continued)

Parts	LT: Taiwan (tkm)	ST: Countries (tkm)	LT: China (tkm)	Carbon Footprint Emissions ($kgCO_2eq$)
Ethanol	(Location to close)	(Location to close)	(Location to close)	(Location to close)
Acetone	255	0	0	0.006217634
Photo resist	255	0	0	0.045695302
Thinner	112.5	0	0	0.015918283
PK-LCG432	(Lack of data)	(Lack of data)	(Lack of data)	(Lack of data)
Soda buffer solution	(Lack of data)	(Lack of data)	(Lack of data)	(Lack of data)
SUM				1.573435201

6.4.4 Summary

The carbon footprint of different stages (Raw material、Manufacturing、Transportation) are shown in Table 38. If we add the result of each stage, it will be the carbon footprint of a TFT-LCD module (B2B Product), as shown in Figure 5. If this 32inch TFT-LCD module is shipped to the downstream company, the carbon footprint of this 32inch TFT-LCD module is 521.4974907 kg CO_2eq, which can be used for calculation in raw material stage of the final product.

Table 38. Product carbon footprint of the TFT-LCD module

A 32inch TFT-LCD Module	Raw material Stage	Manufacturing Stage	Transportation Stage	SUM
	405.292552 kgCO_2eq	114.6315034 kgCO_2eq	1.573435201 kgCO_2eq	521.4974907 kgCO_2eq

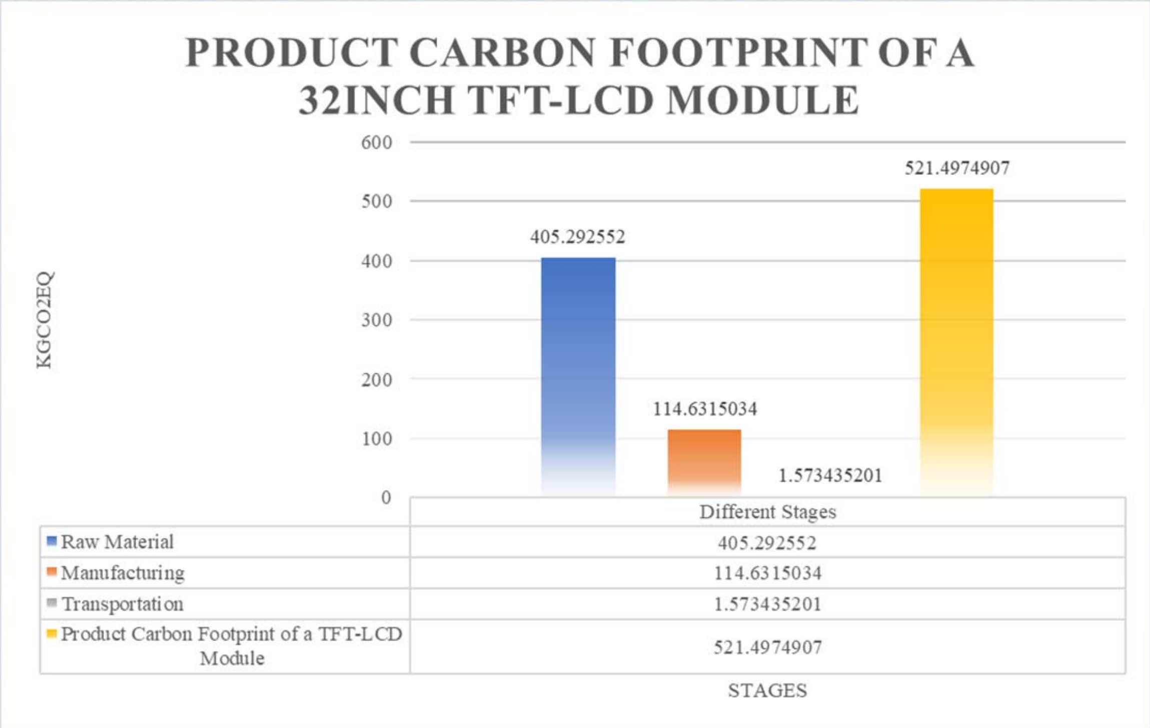

Figure 5. Product carbon footprint of a 32inch TFT-LCD module (B2B)

6.5 TV set Calculation (B2C)

When it comes to display industry, there are many final products related to LCD modules such as TVs, smart phones, tablets and so on. In this case study, a TV is selected to be the final product in display industry. In the case of TV manufactory, it is a downstream company that will choose a suitable LCD module to be their necessary component from raw material stage.

6.5.1 TV set - Raw Material Stage

According to BOM data from AUO Corp., carbon footprint of raw material stage (TV set) will be classified into two parts, EE and MM, as shown in Table 39 and Table 40., and the total carbon footprint of a TV set should add the product carbon footprint of a TFT-LCD module, as shown in Table 41.

Table 39. Carbon footprint of the TV set- EE (Raw material stage)

	Parts	Usage rate per unit of production (kg)	Emission Factor ($kgCO_2eq/kg$)	Usage rate per unit of production ($kgCO_2eq$)
TV set (EE)	LIPS board	0.585	89.74	52.5
	Power cord	0.174	19.54	3.4
	IR board	0.004	203.75	0.815
	Main board	0.236	5.89	1.39
	Adapter board	0.015	41.00	0.615
	Transmitter card	0.01098	41.26	0.453
	Keypad board	0.015	44.93	0.674
	Trumpet	0.36	3.86	1.39
SUM				61.237

Table 40. Carbon footprint of the TV set- MM (Raw material stage)

	Parts		Usage rate per unit of production (kg)	Emission Factor ($kgCO_2eq/kg$)	Usage rate per unit of production ($kgCO_2eq$)
TV set (MM)	Base assembly	Plastic cover	0.711026	3.87	2.75
		PE bag	0.025	2.12	0.0529
		Rubber	0.010974	241.48	2.65
	Cover rear assembly	Cover rear plastic	2.68	4.48	12
		Tape anti-noise	0.007	Lack of data	Lack of data
		Sponge left	0.004	16.25	0.065
		Sponge right	0.0085	2.93	0.0249
		Rubber	0.0008	2.28	0.00182
	Bezel front assembly	Bracket	0.0306	9.48	0.29
		Film protect	0.11	2.53	0.278
		Bezel plastic	0.6644	3.87	2.57
		Plastic cover_A	0.015	86.00	1.29
		Plastic cover_B	0.019	27.63	0.525
		Tape anti-noise	0.0002	9.50	0.0019
		Rubber	0.0008	2.28	0.00182
		Nut	0.0016	5.51	0.00882
	Others	Neck set	0.36	3.28	1.18

Table 40. (Continued)

	Parts		Usage rate per unit of production (kg)	Emission Factor ($kgCO_2eq/kg$)	Usage rate per unit of production ($kgCO_2eq$)
TV set (MM)	**Others**	BOX	0.029	33.55	0.973
		Plastic cover_A	0.12	2.48	0.297
		Plastic cover_B	0.085	14.71	1.25
		Fix tape	0.0005	2.28	0.00114
		Screw_A	0.0025884	5.06	0.0131
		Screw_B	0.0012942	28.98	0.0375
		Screw_C	0.0051768	30.91	0.16
		Screw_D	0.0097065	4.72	0.0458
		Screw_E	0.0006471	104.93	0.0679
		Screw_F	0.0032355	12.05	0.039
		Cable Assembly_A	0.001428	100.84	0.144
		Cable Assembly._B	0.00861	34.49	0.297
		Cable Assembly_C	0.01537	20.56	0.316
		Bracket	1.87	1.87	3.49
SUM					33.11116

Note. *If supply chain companies have done their inventory analysis, the data can be used primarily for calculation. If supply chain companies didn't do the inventory analysis, then the standard database for display industry can be used, as shown in Appendix A.*

Table 41. Carbon footprint of the TV set (Raw material stage)

Parts	$kgCO_2eq$
A 32inch TFT-LCD Module	521.4974907
Raw material for a 32inch TV set - EE and MM	94.34816
SUM	615.8585803

6.5.2 TV set - Manufacturing Stage

In this stage, we directly use the result, 27.1 kgCO2eq, which is provided by AUO Corp., as shown in Table 45.

6.5.3 TV set - Transportation Stage

According to the result, 0.297 $kgCO_2eq$, which is provided by AUO Corp., the carbon footprint of transportation stage will be used directly, as shown in Table 45.

6.5.4 TV set - Use stage

As for different TV set from different companies, there will be different scenarios for use stage. In this case study, there is a standard scenario for different TV set, as shown in Table 42.

Table 42. Standard scenario assumption for different TV's use stage

TV use stage standard scenario	On mode (hours/day)	Stand-by mode (hours/day)	Off mode (hours/day)	Use day per year (days/year)	Life time (years)
	4	20	0	365	6.6

In this stage, we assume that this TV set was used in 2009 (Taiwan) and specification of this TV set (S315XW03 V2) according to the data from AUO Corp. is necessary information for carbon footprint calculation for use stage, as shown in Table 43.

Table 43. Specification of the TV set (S315XW03 V2)

TV set (S315XW03 V2)	
On mode power state (W)	76
Stand-by mode power state (W)	Lack of data
Off mode power state (W)	1.1
Electricity emission factor in 2009 (Taiwan)	0.543 kg CO_2 eq/kwh

As for use stage calculation for the TV set, the following equation should be used [8].

(1) On mode power consumption per year (kwh) = On mode power state x Operation time for On mode x Use days per year

(2) Stand-by mode power consumption per year (kwh) = Stand-by mode power state x Operation time for Stand-by mode x Use days per year

(3) Off mode power consumption per year (kwh) = Off mode power state x Operation time for Off mode x Use days per year

Total carbon footprint for use stage (kg CO_2 eq) = [(1) + (2) + (3)] x life time x local electricity emission factor

Because of lacking data in stand-by mode and zero hour for off mode in standard scenario for use stage, Off mode power state will be substitute with Stand-by mode power state. As the use stage standard calculation mentioned above, the carbon footprint for the TV is shown in Table 44.

Table 44. Carbon footprint of the TV set (Use Stage)

Use stage Calculation	On mode	Stand-by mode	Off mode	Each mode consumption SUM (kwh)
Power (W)	76	1.1	1.1	
hours/day	4	20	0	
Use day per year(days/year)	365			
Consumption(kwh)	110.96	8.03	0	118.99
Life time (years)	6.6			
Electricity emission factor in 2009 (Taiwan)	0.543 kg CO_2eq/kwh (DATA. GOV. TW retrieved from https://data.gov.tw/dataset/30151)			
Total carbon footprint for use stage (kgCO_2eq)	426.4364			

6.5.5 TV set - End-of-Life

There are different assumptions of end-of -life scenarios according to different countries. In this stage, we directly use the result, -9.65 kgCO_2eq, which is provided from AUO Corp., as shown in Table 45.

6.5.6 Conclusion

At last, add up all the carbon footprint of each stages, the result of this assessment will be the product carbon footprint of a TV set, as shown in Table 45. Most of all, this case study and carbon footprint standard calculation can not only help the supply chain company and primary company care about lower carbon footprint design, but increase the comparability, accuracy of the product carbon footprint.

Table 45. Product carbon footprint of the TV set

	Raw Materials Stage	Manufacturing Stage	Transportation Stage	Use Stage	End-of-life Stage	SUM
TV set	615.8585803 $kgCO_2eq$	27.1 $kgCO_2eq$	0.297 $kgCO_2eq$	426.4364 $kgCO_2eq$	-9.65 $kgCO_2eq$	1060.041942 $kgCO_2eq$

6.6 Suggestion

There are some problems which we can find from this assessment. First, the BOM data from AUO Corp. lack the information of transportation and location of each supply chain companies, so we can't calculate the carbon footprint of the TV set in transportation stage precisely. In fact, choosing different supply chain companies will change the result in transportation stage of a 32inch TFT-LCD module, and so as in TV set which choose different TFT-LCD modules will change the product carbon footprint of the TV set. On the other hand, the information about greenhouse gas emission of the manufacturing facility, area of input glass, and some other information are from other literature. However, we ignored the manufactory who has module process and Scope 3 emissions because of the lack of data. It is reasonable for this research to ignore those situations. On one hand, the carbon footprint inventory analysis for primary company, as mentioned before, is only obligated to do Scope 1 and Scope 2 emissions because the coverage of Scope 3 is too complicated to calculate carbon footprint emissions and module process usually does not contain much carbon footprint emissions compared to the array and cell process. On the other hand, the calculation of Scope 3 may cause repetitive computation for transportation stage. Therefore, it is easy and simply to ignore those two parts. Second, the carbon footprint of the TV set in the use stage is not accurate because the specification of the TV set is not completed. However, we can compare carbon footprint with different stages, as shown in Figure 6. In this assessment by using this carbon footprint standard, the result of use stage is much lower than the result of raw material stage. Under normal circumstances, we still can find that raw material and use stage have the highest carbon footprint emissions. To date, the type of backlight unit is almost substitute LED with CCFL in raw material stage and there are many regulations about limited consumption in use stage (On mode、Stand-by mode、Off mode) such as WEEE. Consequently, the carbon footprint in raw material stage of a TFT-LCD module will be different from now, and the product carbon footprint of the TV set in the present use stage will much lower than in 2009. In the future, there are going to be some restrict rules about product design from raw material stage. Third, there are so many end-of-life scenarios about TV sets, we hope that every designer should design their own recycling strategies in order to let carbon footprint calculation of the TV set become more realistic. Finally, there should be another product in the same level for comparison in order to verify this standard.

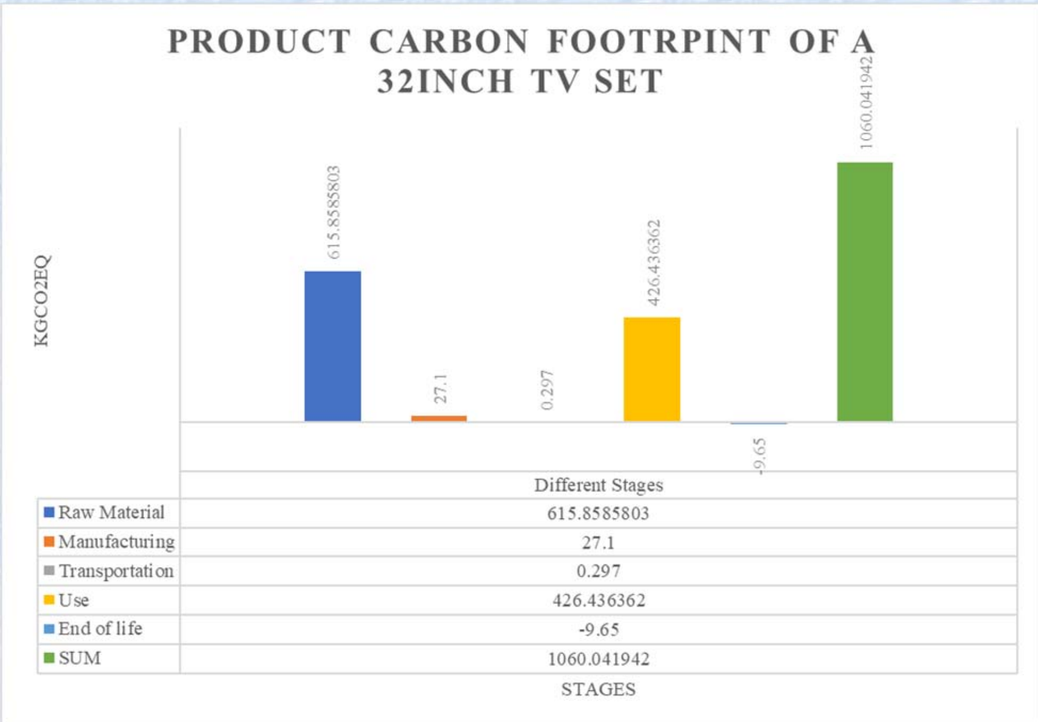

Figure 6. Carbon footprint of a 32inch TV - Different Stages Evaluation

7 Allocation Methods for IT Products (Appendix C)

The following content, feasible allocation methods for supply chain companies, are transferred from Electronic Industry Citizenship Coalition (EICC) [2].

7.1 PCBs

Printed circuit boards (PCBs) are ubiquitous throughout electronic products. Besides, the final component that is present in an end-user device is a printed circuit board assembly (PCBA) that includes the board itself as well as both passive and active electronic mounted components such as integrated circuits, capacitors, transistors, resistors, diodes and so on.

Allocation is performed most typically by **board area** and **layer area** (final board area x number of layers) and there are two feasible ways to allocate carbon footprint impact for PCB:

1. **MCF_{PCB} (kg CO_2eq) = [$GHG_F/(A_{layer\_total})]x(A_{PCB\_Board} x L_{PCB})$**

   where

MCF_{PCB} = the manufacturing carbon footprint of a single PCB in a product (kg CO_2eq)

GHG_F = the total manufacturing facility greenhouse gas emissions in a year (kgCO_2eq)

A_{layer_total} = the total area of layers of board produced in the facility for that year (in m^2)

A_{PCB_Board} = the specific PCB board area for the product being studied (in m^2)

L_{PCB} = the layers of PCB for the product being studied

2. **MCF_{PCB} (kg CO_2eq) = $[GHG_{scope1}/(A_{board\_total})] x (A_{PCB\_Board}) + [GHG_{scope2}/(A_{layer\_total})] x (A_{PCB\_Board} x L_{PCB})$**

where

MCF_{PCB} = the manufacturing carbon footprint of a single PCB in a product (kg CO_2eq)

GHG_{scope1} = the total Scope 1 manufacturing facility greenhouse gas emissions in a year (kgCO_2eq)

GHG_{scope2} = the total Scope 2 manufacturing facility greenhouse gas emissions in a year (kgCO_2eq)

A_{layer_total} = the total area of layers (inner and outer) of board produced in the facility in that year (in m^2)

A_{board_total} = the total area of board produced in the facility in that year (in m^2)

A_{PCB_Board} = the specific PCB board area for the product being studied (in m^2)

L_{PCB} = the layers of PCB for the product being studied

7.2 PCBA

Contract manufacturing facilities often perform the activity of taking a bare circuit board and the components of an ICT product, mounting the components to the board, permanently securing the components with solder and/or adhesive, possibly singulating panels of products into finished items, and testing the products in one or more ways. Assembly and test describe the two major manufacturing steps that transform many parts into one conjoined assembly ready for use. The final product of the assembly process is known as“printed circuit assembly”(PCA), or a“printed circuit board assembly”(PCBA).

There are three feasible ways to allocate carbon footprint impact of PCBA:

1. **$MCF_{A\&T}$ (kg CO_2eq) = W_{PCBA}x(GHG_F/W_{tot_PCBA})**

   where

$MCF_{A\&T}$ = the assembly and test carbon footprint of a specific product (kg CO_2eq)
GHG_F = the total manufacturing facility greenhouse gas emissions in a year (kg CO_2eq)
W_{PCBA} = the weight of the specific PCBA that emissions are being determined for (kg)
W_{tot_PCBA} = aggregate **PCBA** weight of all products manufactured in a reported year (kg)

2. **$MCF_{A\&T}$ (kg CO2e) = (W_{FA}x(GHG_F/W_{tot}))/PCT_{elec}**

   where

$MCF_{A\&T}$ = the assembly and test carbon footprint of a specific product (kg CO_2eq)
GHG_F = the total manufacturing facility greenhouse gas emissions in a year (kg CO_2eq)
W_{FA} = the **completed** weight of the specific product (kg)
W_{tot} = aggregate **completed** weight of all products manufactured in reported year (kg)
PCT_{elec} = an average percentage of the weight of the electronics only to the total weight of the shipped product

3. $MCF_{A\&T}$ (kg CO_2eq) = (GHG_F/N_{tot_PCBA})

where

$MCF_{A\&T}$ = the assembly and test carbon footprint of a specific product (kg CO_2eq)

GHG_F = total facility greenhouse gas emissions in a year (kgCO_2eq)

N_{tot_PCBA} = aggregate count of all **PCBA**s manufactured in reported year (kg)

7.3 ICs

Integrated Circuits (ICs) are ubiquitous throughout electronic products. They range quite dramatically in complexity, package type, area and stacking within the die.

There are two feasible ways to allocate carbon footprint impact of ICs:

1. **MCF_{IC} (kg CO_2eq) = [$GHG_F/(A_{output})$]x(A_{IC})**

   where

MCF_{IC} = the manufacturing carbon footprint of a single IC - cradle to gate (kg CO_2eq)
GHG_F = the total manufacturing facility greenhouse gas emissions in a year (kg CO_2eq)
A_{output} = the total good wafer out (in cm^2)
A_{IC} = the total area of a specific IC (in cm^2)

2. **MCF_{IC} (kg CO_2eq) =[$GHG_F/(A_{output}xML_{fab})$]x($A_{IC}xML_{IC}$)**

   where

MCF_{IC} = the manufacturing carbon footprint of a single IC - cradle to gate (kg CO_2eq)
GHG_F = the total manufacturing facility greenhouse gas emissions in a year (kg CO_2eq)
A_{output} = the total good wafer out (in cm^2)
ML_{fab} = number of mask layers for that facility
ML_{IC} = number of mask layers for the specific IC
A_{IC} = the total area of a specific IC (in cm^2)