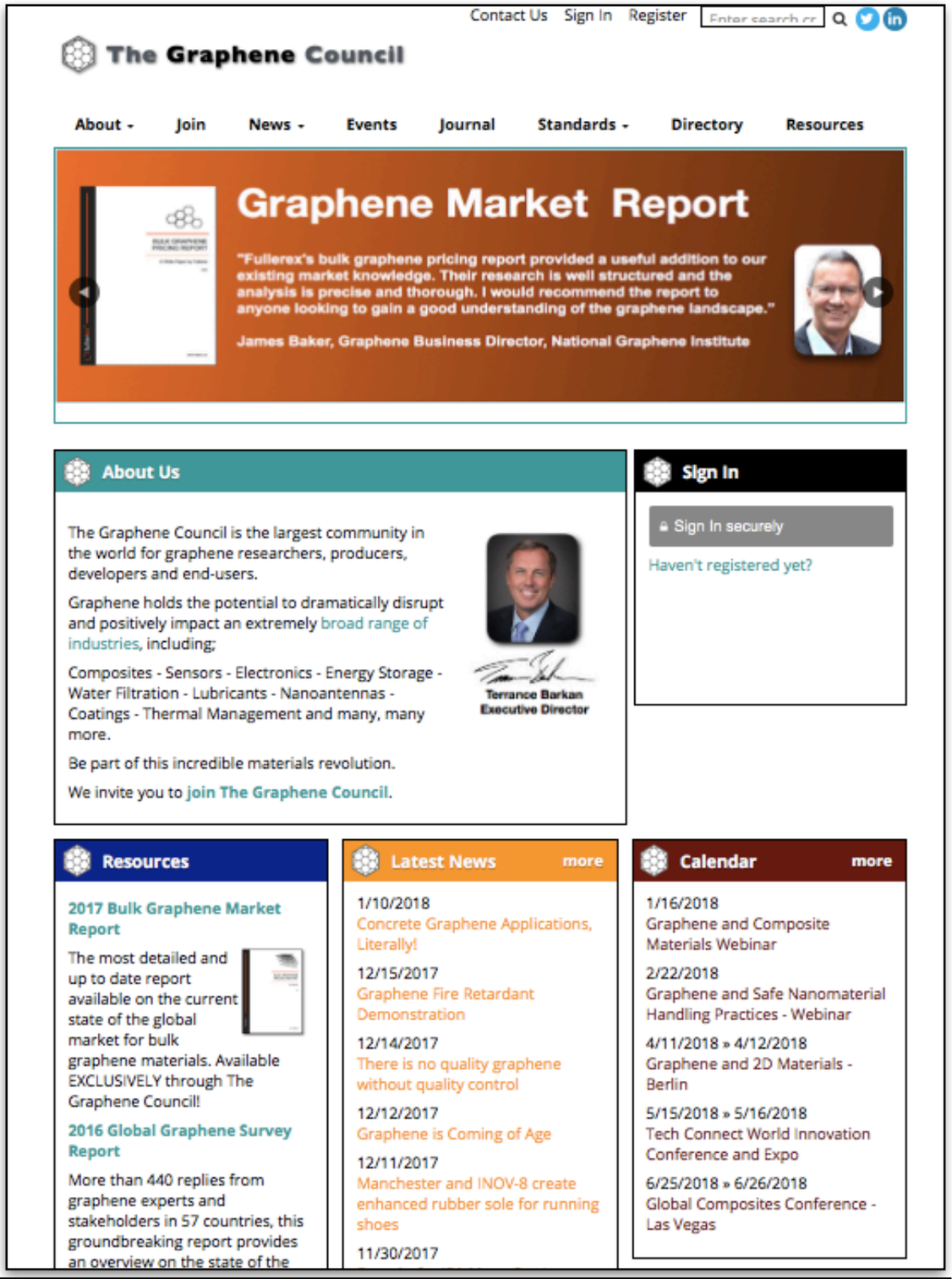
Survey of Graphene Materials Used in Various Applications and the Most Relevant Material Characteristics

The Graphene Council

About The Graphene Council

The Graphene Council is;

- **The largest community in the world for graphene researchers, developers, producers and other stakeholders.**
- **Formal members of the ISO/ANSI/IEC Graphene Standards development working groups.**
- **Produce original information, content and reports on the state of the graphene industry and takes a lead in facilitating commercialization through education and networking.**



Graphene News and Information

The Graphene Council

- **Weekly graphene intelligence newsletter.**
- **Graphene Technology peer reviewed journal published by Springer Nature.**
- **Graphene Bulk Pricing and other market oriented reports.**
- **The most in-depth source of information on graphene commercialization**

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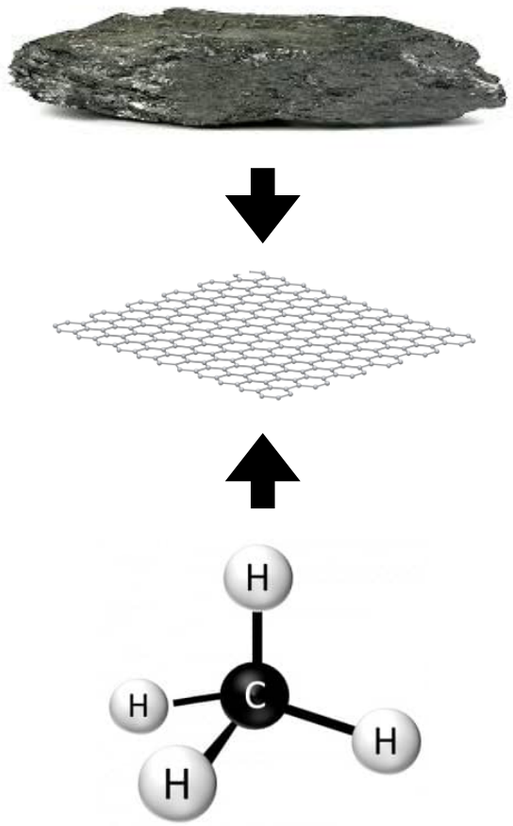
Types of Graphene Materials Used in Target Applications

Forms of Graphene

Production

- Graphene production methods can be classified broadly as “Top Down” and “Bottom Up”.

- “Top Down” methods start with a feedstock material such as graphite and through various methods (physical, electrical, chemical, etc.) exfoliate individual layers of carbon.



- “Bottom Up” methods start with a carbon feedstock such as methane gas that under controlled conditions (such as Chemical Vapor Deposition-CVD) is deposited on a substrate material (such as copper) in single or multiple layers.

Forms of Graphene

- A wide range of commercially available materials are referred to as “graphene”
- “ISO/TS 80004-13:2017(en) Nanotechnologies — Vocabulary — Part 13: Graphene and related two-dimensional (2D) materials” recognizes material up to and including 10 carbon layers as “graphene”
- IEC Blank Material Specification for Graphene
- ISO TC229 / IEC TC113 Graphene Characterization Matrix

Number of Carbon Layers	Description
1	CVD, Mono-layer or “Pristine” Graphene
1 - 3	Very Few Layer Graphene (vFLG)
2 - 5	Few Layer Graphene (FLG)
2 - 10	Multi-Layer Graphene (MLG)
> 10	Exfoliated graphite, “Graphene nanoplatelets” (GNP) or “nano graphite”

Graphene Characterization

- **Besides the number of carbon layers, additional characteristics define the material.**
  - **<u>Graphene Oxide (GO)</u> - a compound of carbon, oxygen and hydrogen (typically approx. 65% carbon / 35% oxygen by weight).**
  - **<u>Reduced Graphene Oxide (rGO)</u> - Graphene Oxide in which removes much of the oxygen content resulting in approximately 95% carbon by weight.**
  - **<u>Graphene Powder, Solution or Paste</u> - Graphene material can be prepared in various physical forms including as a dry (usually black) powder, in solution (e.g. water or alcohol) or in a paste form (often as a dull reddish brown color).**
  - **<u>Graphene Nano Platelets (GNPs)</u> - GNPs typically have thickness of between 1 nm to 3 nm and lateral dimensions ranging from approximately 100 nm to 100 µm.**
  - **<u>Functionalized Graphene</u> - Chemical functionalization (adding specific elements to the surface of the graphene) is important in many applications where untreated graphene would be difficult or impossible to work with.**

Graphene “Quality”

There is widespread confusion about the definition of “Quality Graphene”.

- **Material that is not suitable for one application may be ideal for another.**
- **Graphene “defects” may actually enhance the efficacy of the material for a particular application.**
- **There is no such thing as a reference material for graphene at this time.**
- **Because load factors can be quite low, the price of the material is not the most significant factor when selecting source material.**
- **The primary factor is in selecting a trusted, competent and consistent supplier of the material that understands your application areas.**

Review of Graphene Material Data Sheets from Commercially Available Products

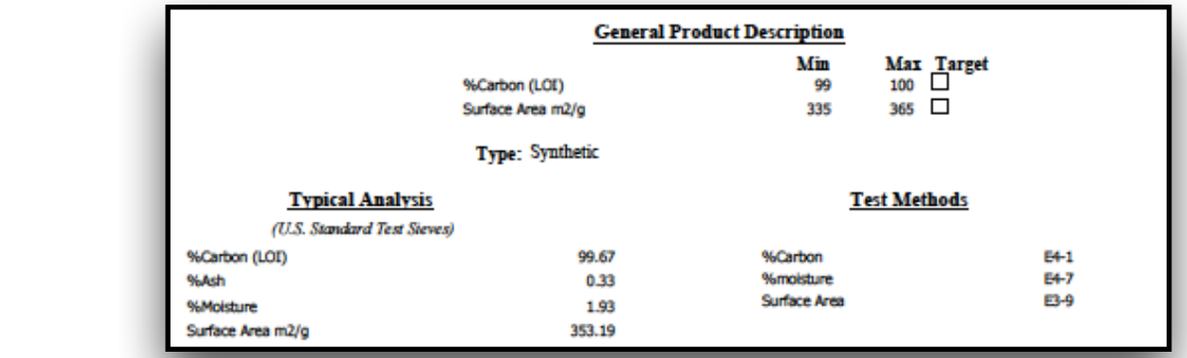
Lack of Transparency

More than 60 different graphene material data sheets were reviewed.

More than 45 different discreet characteristics or pieces of material information were listed one or more times for one or more of the products.

<u>Not a single material characteristic was shared across every product.</u>

The most commonly reported characteristics were provided for <u>fewer than 75%</u> of the products we analyzed.



General Product Description

	Min	Max	Target
%Carbon (LOI)	99	100	☐
Surface Area m2/g	335	365	☐

Type: Synthetic

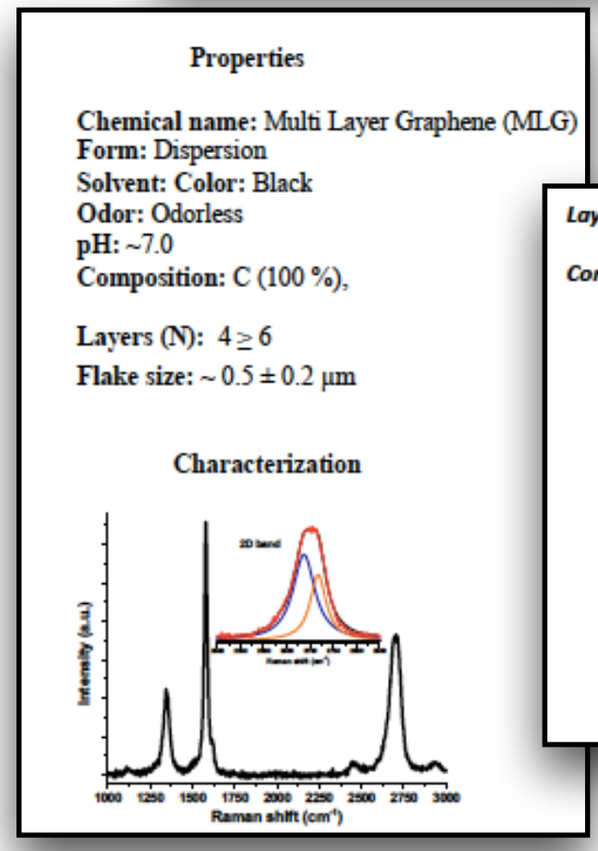
Typical Analysis

(U.S. Standard Test Sieves)

%Carbon (LOI)	99.67
%Ash	0.33
%Moisture	1.93
Surface Area m2/g	353.19

Test Methods

%Carbon	E4-1
%moisture	E4-7
Surface Area	E3-9

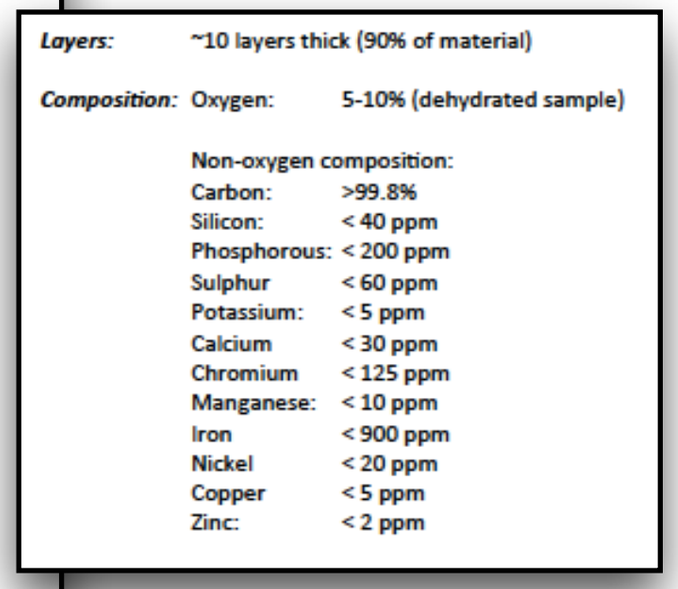


Properties

Chemical name: Multi Layer Graphene (MLG)
Form: Dispersion
Solvent: Color: Black
Odor: Odorless
pH: ~7.0
Composition: C (100 %),

Layers (N): $4 \geq 6$
Flake size: $\sim 0.5 \pm 0.2$ µm

Characterization



Layers:	~10 layers thick (90% of material)	
Composition:	Oxygen:	5-10% (dehydrated sample)
	Non-oxygen composition:	
	Carbon:	>99.8%
	Silicon:	< 40 ppm
	Phosphorous:	< 200 ppm
	Sulphur	< 60 ppm
	Potassium:	< 5 ppm
	Calcium	< 30 ppm
	Chromium	< 125 ppm
	Manganese:	< 10 ppm
	Iron	< 900 ppm
	Nickel	< 20 ppm
	Copper	< 5 ppm
	Zinc:	< 2 ppm

Graphene Data Sheets

List of Characteristics on Material Specification Sheets (Alphabetical order)

Ash by WT%
Average Lateral Dimensions (x&y) um
Average Through Plane Dimension (z) nm
Bulk resistivity
Calcium ppm
Carbon %
Chromium ppm
Color
Combustion point in Degrees C
Copper ppm
Electrical Conductance
Functional Groups AT%
Hydrogen by WT%
IMAGES (Microscopy)
Iron ppm
Manganese ppm

Metallic Content ppm
Moisture % (Powders Only)
Nickel ppm
Nitrogen by WT%
Number of Layers
Odor
Oxygen by WT%
Particle Size Distribution um
pH
Phosphorous ppm
Porosity nm
Potassium ppm
Primary Sheet Aspect ratio
Purity Level
RAMAN Scans (D, G and 2D Bands)
Relative Gravity g/cc

Residual Acid Content
Salts ppm
Sheet Resistance Ohm/
Shelf Life
Silicon ppm
Solids %
Solvent
Specific Surface Area m2/g
Sulphur ppm
Tap Density g/cm3
Tensile Modulus
Thermal Conductivity (watts/meter-K)
True/Bulk Density g/cm3
Visual
Zinc ppm

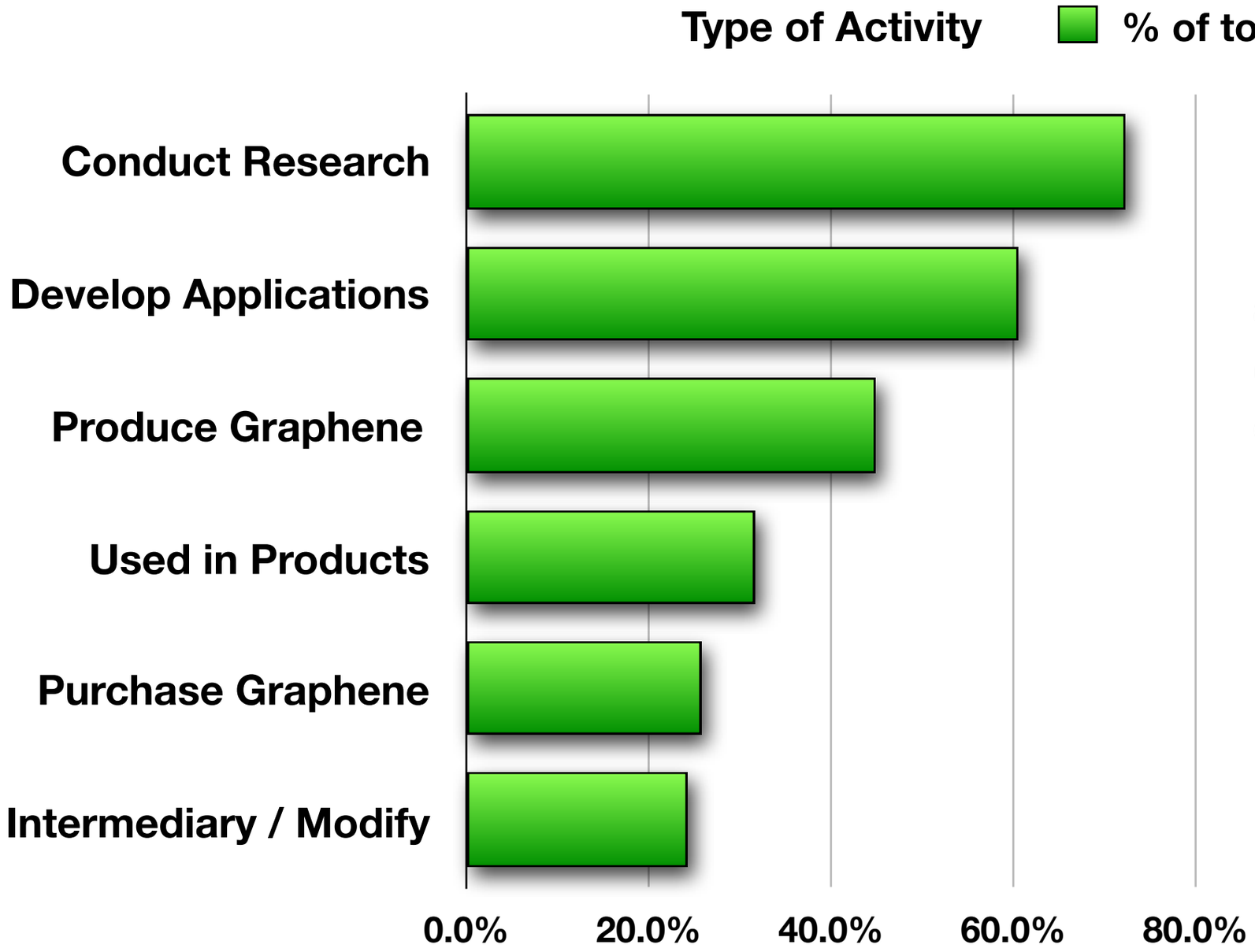
Graphene Characterization Survey

The Graphene Council received 373 replies to our graphene characterization survey. The objectives of the survey included to;

1. **Understand what types of graphene are being used,**
2. **For which types or categories of applications and,**
3. **Which material characteristics are of highest importance or value.**

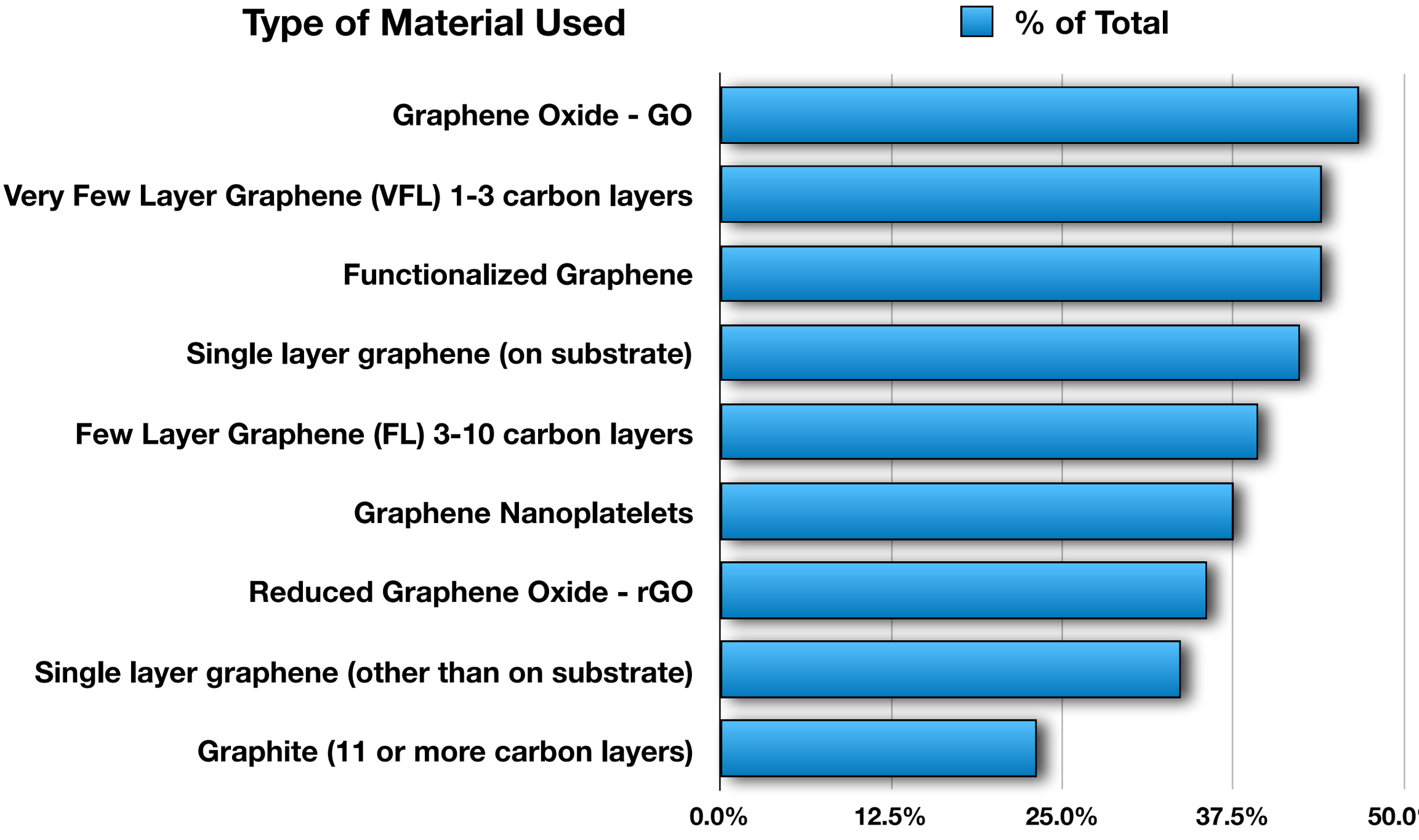
In addition, we asked respondents to declare if they were a graphene producer, researcher, application developer or end user.

Graphene Characterization Survey



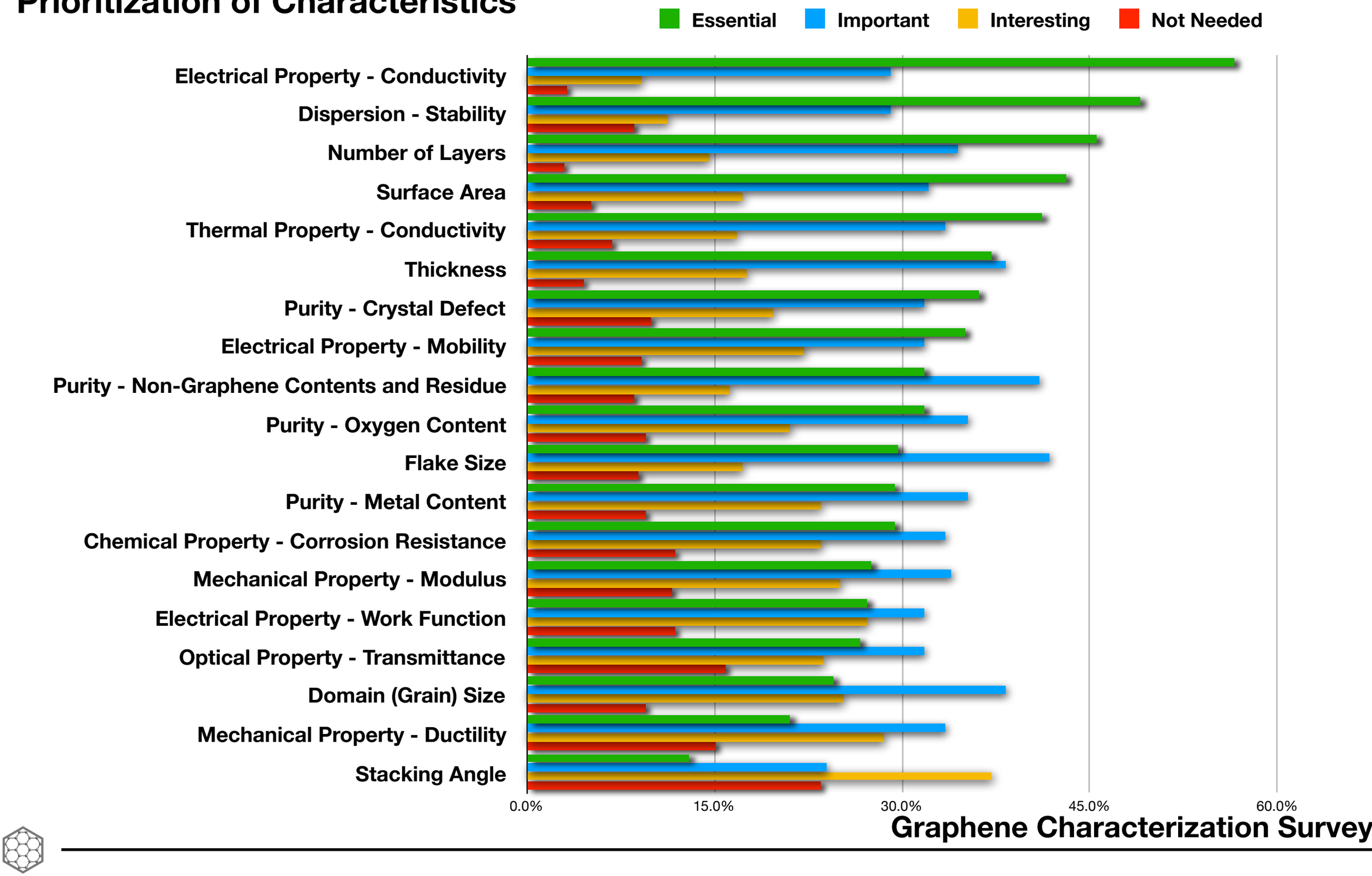
Note: Respondents were allowed multiple responses (i.e. they may be a Producer, Conduct Research and Develop Applications

Graphene Characterization Survey



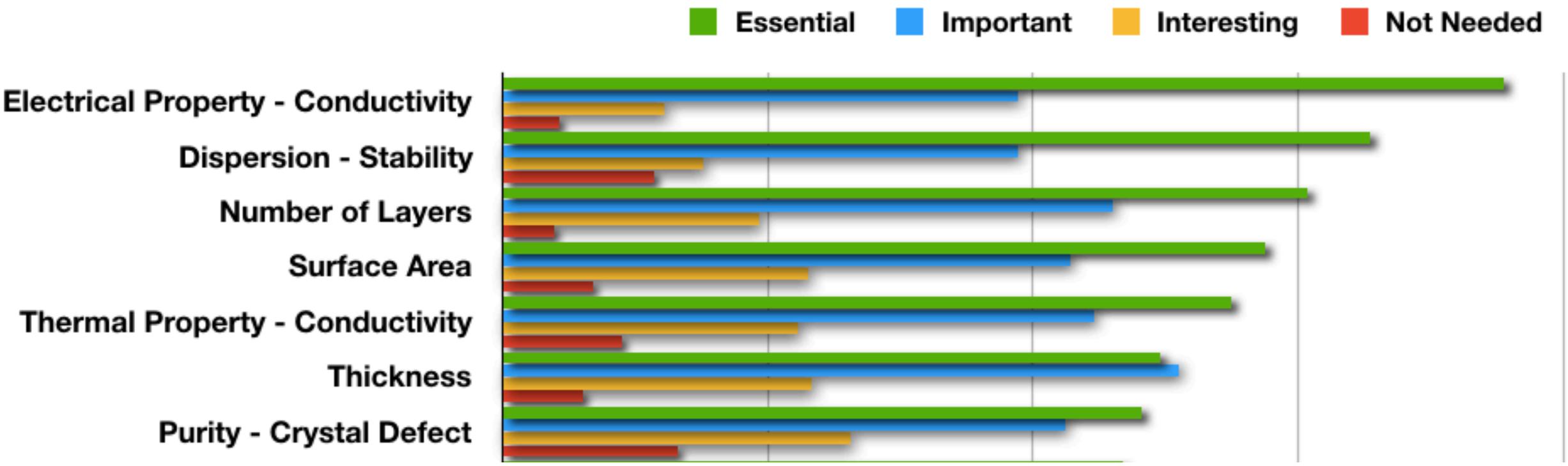
Graphene Characterization Survey

Prioritization of Characteristics



Graphene Characterization Survey

Prioritization of Characteristics

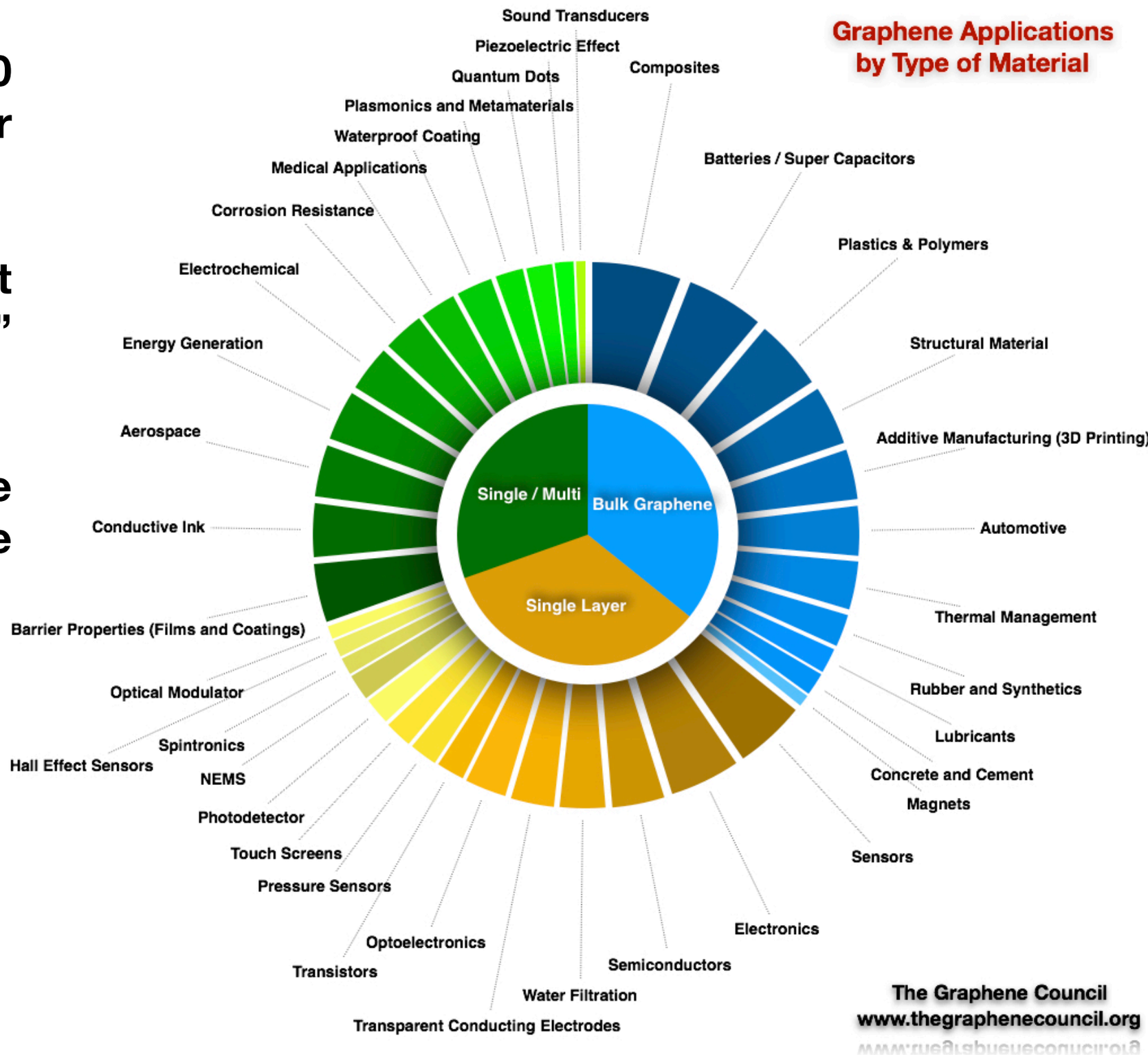


Graphene Applications

There are more than 40 major applications areas for graphene.

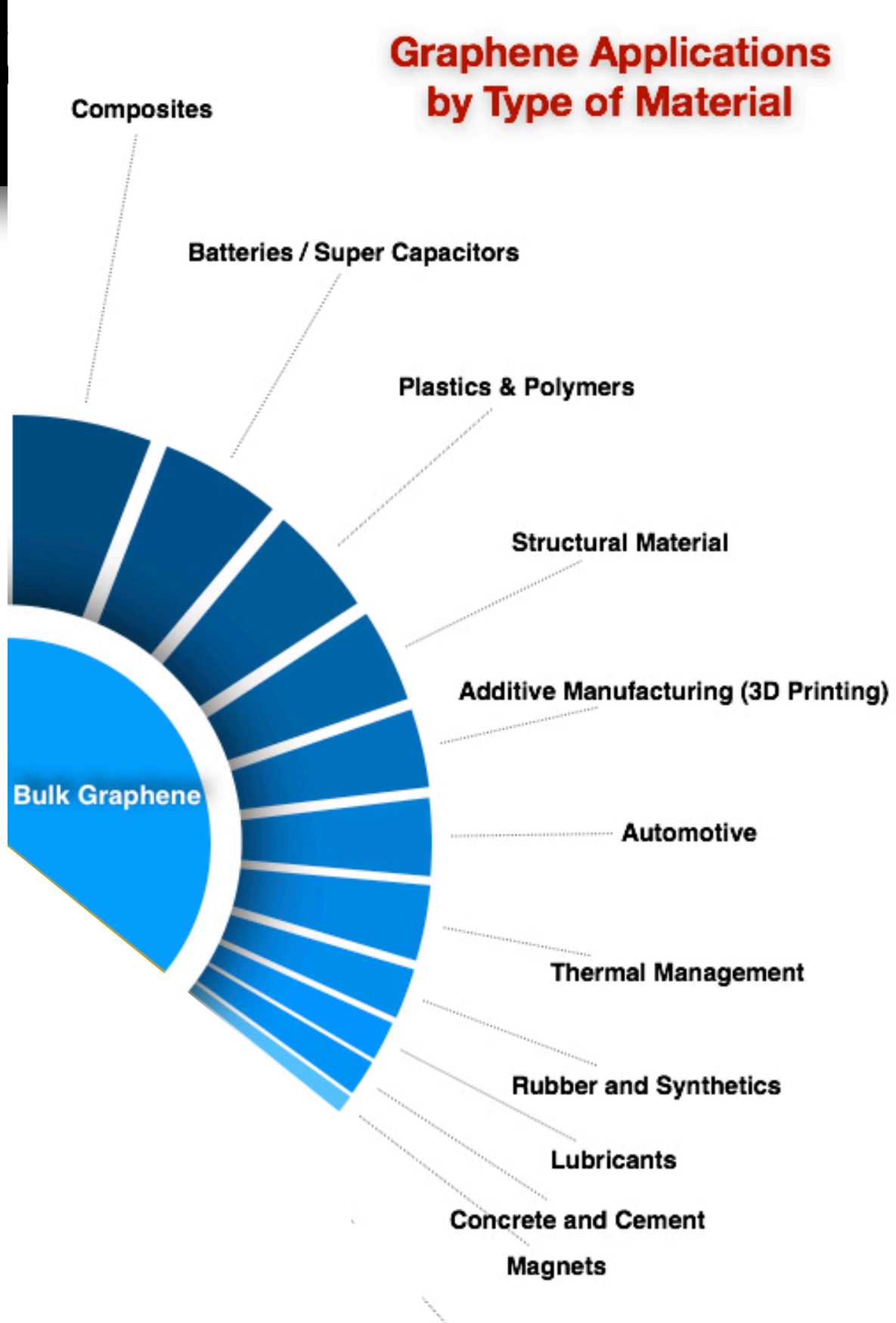
‘Composites’ are the largest application area for “bulk” graphene.

Sensors and electronics are key applications for single layer graphene.



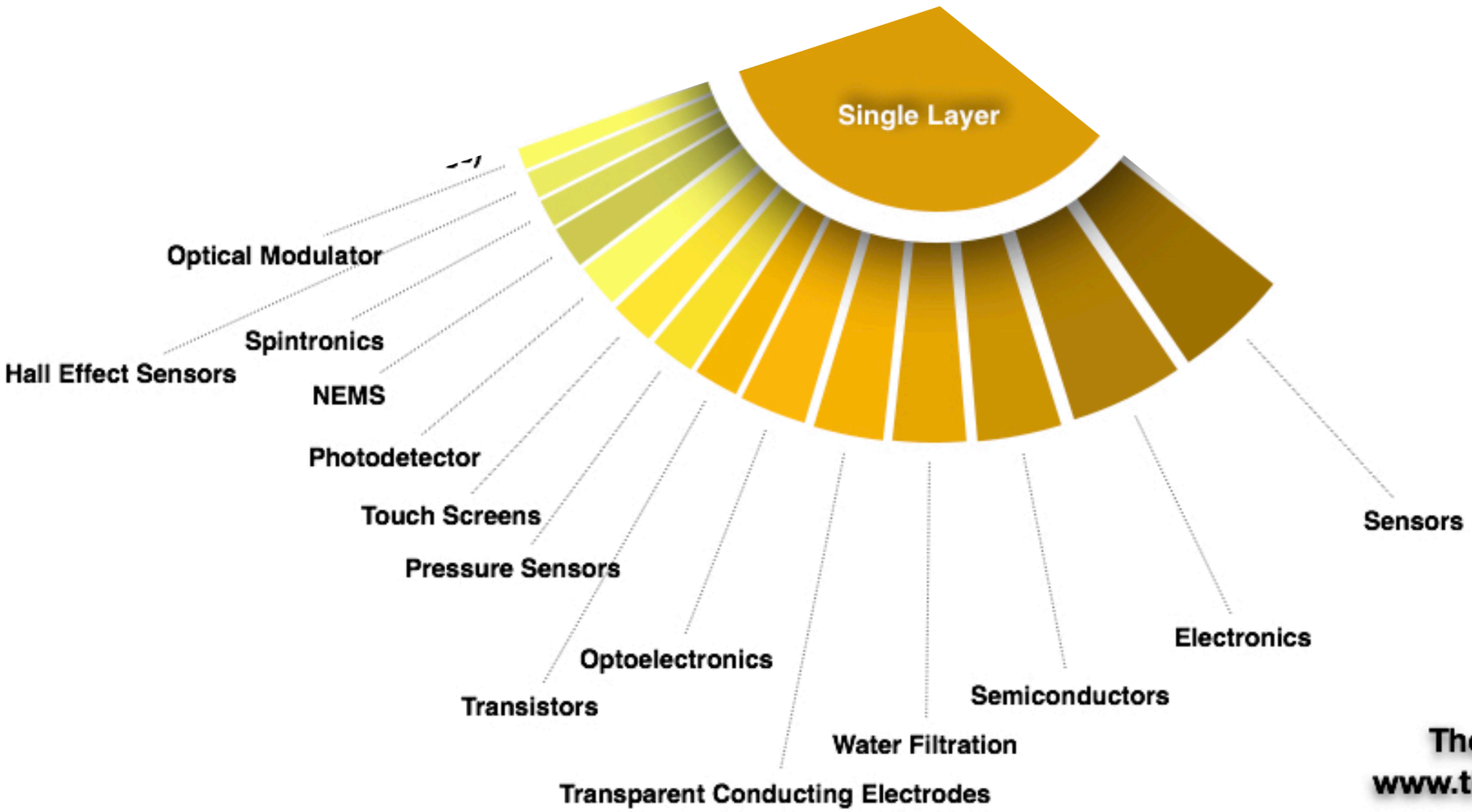
Applications

“Bulk Graphene” includes Graphene Oxides, GNP’s and multi-layer graphene materials usually in the form of powders, suspensions on incorporated in ‘master batch’ host materials



Graphene Applications

‘Single Layer’ is almost exclusively CVD or Epitaxial Graphene.



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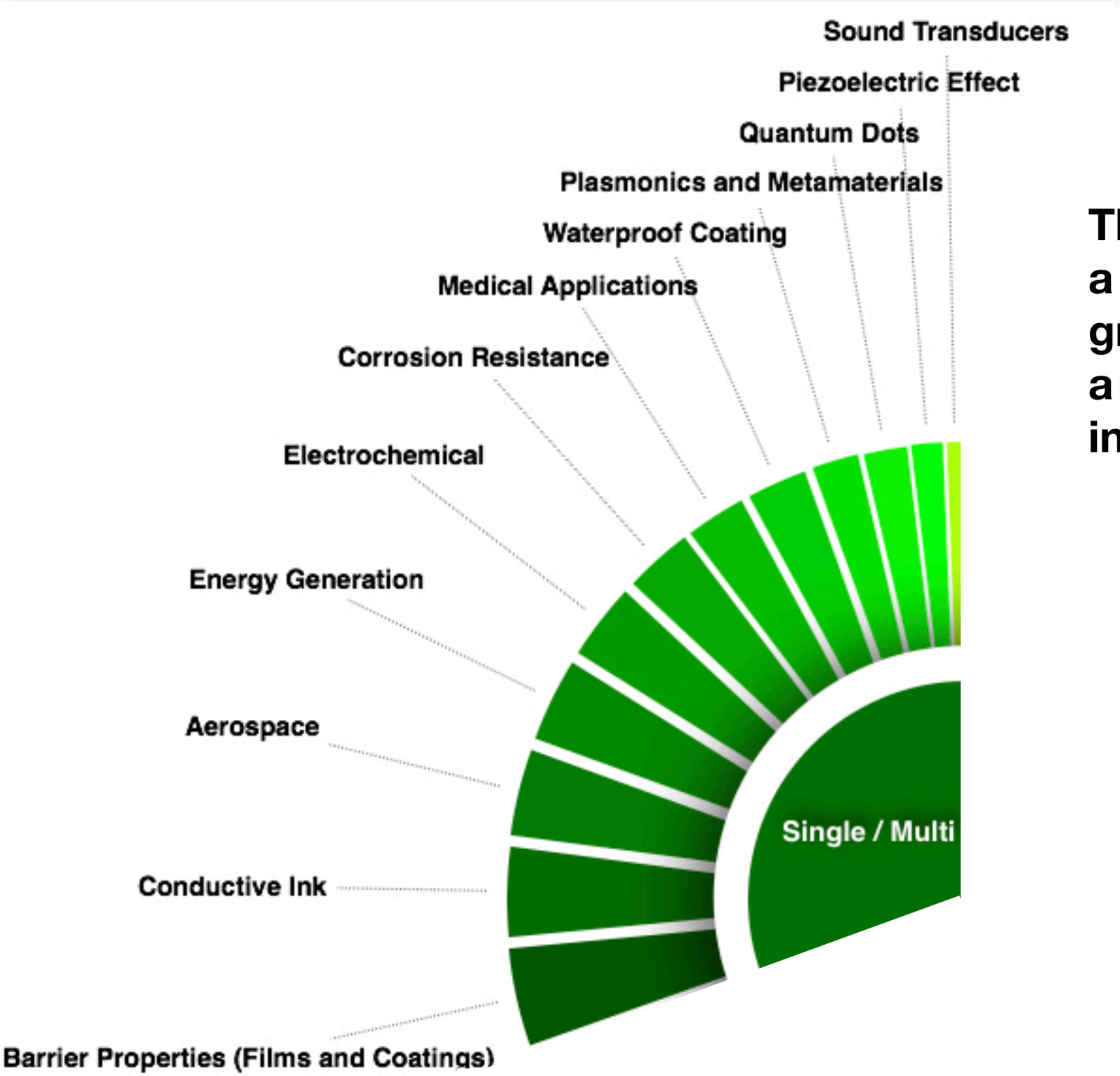
Graphene Applications



These applications may use a combination of types of graphene or use single layer and multilayer material interchangeably.

Graphene Characterization Survey

Key Characteristics & Testing Methods

Draft recommendation of a minimum set of material specifications for materials listed as “Graphene” (GO, rGO, CVD, GNPs, FLG, etc.)

Characteristic	Testing Method	Reporting Format
Number of carbon layers	RAMAN / TEM	Number of carbon layers (minimum and maximum) and distribution (e.g. 10% mono-layer, 50% 2-3 layer, 40% 4-8 layer).
Average Through Plane Dimension	RAMAN	Average Through Plane Dimension (z axis) in nm
Average lateral dimensions of the graphene flakes or nano platelets	TEM / SEM /	Average lateral dimensions (x&y axis) in µm
Specific Surface Area	BET (ISO 9277:2010)	Specific Surface Area expressed as m2/g
Chemical analysis of functionalized graphene	XPS	Report for each element detected either by weight as a percentage of the sample or in ppm.
Carbon content	XPS	Report the amount of Carbon as a percentage of the total weight of the material.
Oxygen content	XPS	Report the amount of Oxygen as a percentage of the total weight of the material.
Raman Scan Images	RAMAN	Graphic illustration of the RAMAN Scans (D, G and 2D Bands).
Microscopy images	TEM / SEM	At least one image of the material at a sufficient magnification to visualize the structure with a scale overlaid on the image.

Questions?

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