

**Brandenburg University of Technology  
Cottbus**



**Faculty of Environmental Sciences and  
Process Engineering**

**International Course of Study: Environmental  
and Resource Management (Ph.D.)**

## **PhD Thesis**

# **Thermal Recycling of Plastic Waste Using Pyrolysis- Gasification Process for Energy Production**

A thesis approved by the Faculty of Environmental Sciences and Process Engineering at the Brandenburg University of Technology in Cottbus in partial fulfilment of the requirement for the award of the academic degree of Doctor of Philosophy (Ph.D.) in Environmental Sciences.

by

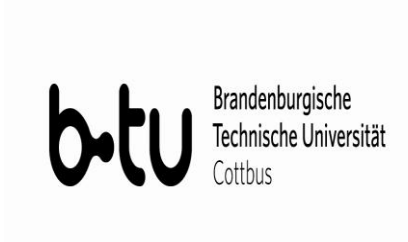
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**Brandenburgische Technische Universität  
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**Fakultät für Umweltwissenschaften und  
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## **DOKTORARBEIT**

### **Thermische Nutzung von Kunststoffabfällen in Kleinanlagen unter Verwendung des Pyrolyse- und Vergasungsprozesses**

Von der Fakultät für Umweltwissenschaften und Verfahrenstechnik der Brandenburgischen Technischen Universität Cottbus zur Erlangung des Akademischen Grades eines Doktors der Philosophie (Ph.D.) in Umweltwissenschaften genehmigte Dissertation

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## Declaration

I declare that this dissertation is a result of my exerted efforts and hard work. The research has been carried out at the Brandenburg University of Technology (BTU) Cottbus under the framework of the PhD program in Environmental and Resource Management under the supervision of Prof. Dr. -Ing. habil. Günter Busch of the Chair of Waste Management, and Prof. Dr. rer. nat., habil. Hans-Jürgen Voigt, Chair of Environmental Geology at BTU Cottbus, Germany.

This thesis has never been submitted in part or in whole for a degree at any institution. References made to other scientific works or sources have been duly cited and acknowledged.

*Forbidgteke*

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Forbid George Teke

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### ***A final word***

I am aware more than ever before of how much I have learned from this study and will continue to learn from my lecturers, respondents, other authors and readers involved in this field of study. If you have a comment or suggestion for making this research work better, please email me at: [gtforbid@yahoo.com](mailto:gtforbid@yahoo.com).

## **Dedication**

This work is dedicated to my mother, Feh Helen; late father, Forbid Joseph Tetuh and late aunt Anyah Ebokwa for whom I owe my entire life and success.

## Abstract

The disposal of mixed waste in landfills, dump sites and open burning without material and energy recovery leads to resource loss, causes health problems, pollution and littering. Increasing energy demand for industrial and domestic application with rising costs due to scarcity motivates a constant search for alternative clean energy sources. Recovering energy from waste presents various incentives e.g. creating jobs, alleviating poverty, combating and mitigating climate change, protecting the environment and reducing dependence on traditional fuels sources. Unfortunately, most non-biodegradable, high calorific value waste fraction (plastics) has little or no application in most developing world communities. Hence, plastics end up in landfills, surface waters and ocean bed with serious negative impact on terrestrial and aquatic biodiversity. Plastic waste with high calorific value (36-46MJ/kg) occupies the greatest portion of landfill space given their very slow degradability. When openly burned, plastics produce high pollutants such as VOCs, PAHs and PCDD/F (dioxins). The formation of these pollutants is not inherent of the polymers but is consequent of limitations of the combustion process. Hence, using an appropriate technology to transform waste plastic to a hot gaseous mixture which is burned in-situ produces enormous amount of energy without pollution. Based on this hypothesis, the study objectives accomplished were to:

1. Characterise, quantify and classify waste fractions and plastic components common in commingled MSW by manual sorting
2. Evaluate options for sustainable plastic waste management especially for developing countries
3. Design, construct, test and optimize an appropriate technology that applies pyrolysis and gasification processes to convert non-PVC plastic waste to energy
4. Assess the efficiency of the technology based on the functioning, the engineering, mass and energy analysis including socioeconomic and environmental impacts

An integrated methodology involving review of current literature, field and laboratory experiments on mixed waste and plastic waste analysis was used. In addition, the pyrolysis-gasification technology (PGT) was conceptualised, designed, constructed, tested and optimised at BTU Cottbus in Germany, Lagos in Nigeria and Dschang in

Cameroon. Field studies involving natural observation, interviews, personal discussions and visits to waste management organisations and disposal sites were conducted in various cities in the three case study countries. A resource-oriented manual sorting using the resource-recovery scavenging approach (RESA) simulating integration of scavenger's activities in waste sorting was conducted at BTU and Lagos Nigeria. Major results obtained include:

- Characterization, quantification and classification of a dry sample of commingled MSW at Cottbus, Germany gave major waste fractions in order of decreasing abundance as 23.15% of residue waste, 19.75% of paper and cardboards, 17.80% of plastics, 14.63% of textiles and diapers, 10.06% of food waste and 9.55% of glass. An overall 33.21% of waste sample is compostable for manure, 52.2% usable as feedstock in the PG technology and 99.81% of total sample having a material or energy recovery potential. In Lagos, Nigeria main fractions were 29% of plastics, 36% of residue waste, 17% of soil/sand, 7% of paper with overall 41% usable as feedstock in PG technology, 39% compostable, 3% of recyclable (metal and glass). Sand can be recovered from the soil/sand fraction for construction. Excluding the sand/soil mixture, 83% of the total waste sample has potential for material and energy value.
- An appropriate technology that applies principles of pyrolysis and gasification to convert non-PVC plastic waste to energy was designed, constructed, tested and optimized with respect to: (i) Successful functioning with conversion of averagely 98.51% of input constituting of 82.78-98.21% of charcoal and 96.72-99.27% of plastic to heat energy (ii) Evaluation of socioeconomic and environmental impacts based on pyrolysis and exhaust gas and ash residue analysis showed absence of VOCs, heavy metals and pollutant organic and inorganic compounds; (iii) Safety and risk assessment to indoor pollution is very low due single directional flow of exhaust gases through system based on natural draft; (iv) Assessment of the WTA and WTP indicated that 94% of respondents in Lagos, Nigeria and Porto Novo, Benin were willing to accept and pay for this technology. Evaluation of options for sustainable plastic waste management with energy recovery using PG technology offers the best cost-effective and affordable choice for

most developing countries due to its pollution-free ability, internal recycling of the energy, low cost and zero indoor and outdoor air pollution. Using the PG technology improves local communities' ability to achieve clean, efficient and safe cooking and heating energy with potential for combined heat and power generation. This scientific and technological approach can be applied to improve fuel combustion efficiency while reducing flue gas scrubbing costs in engines and incineration plants.

## Zusammenfassung

Die Entsorgung von gemischten Abfällen in Deponien, Ablagerungsplätzen und das offene Verbrennen ohne jegliche stoffliche und energetische Verwertung führt zu Ressourcenverlusten, Gesundheitsproblemen, Umweltverschmutzung und Vermüllung. Wachsender Energiebedarf für industrielle und häusliche Anwendung mit steigenden Kosten aufgrund ihrer Knappheit regt die ständige Suche nach alternativen, sauberen Energiequellen an. Energierückgewinnung aus Abfall stellt verschiedene Anreize wie z.B. die Schaffung von Arbeitsplätzen, Bekämpfung der Armut, Bekämpfung und Eindämmung des Klimawandels, den Schutz der Umwelt und die Verringerung der Abhängigkeit von traditionellen Brennstoffquellen. Unglücklicherweise finden die meisten nicht-biologisch abbaubaren, heizwertreiche Abfallfraktionen (Kunststoffe) wenig oder gar keine Anwendung in den meisten Gemeinden. Infolgedessen enden Kunststoffe auf Deponien, in Oberflächengewässern und Meeresböden, mit gravierenden negativen Auswirkungen auf die terrestrische und aquatische Biodiversität. Kunststoffabfälle mit hohen Heizwerten (36-46MJ/kg) nehmen den größten Teil des Deponieraumes ein, in Anbetracht ihrer sehr langsamen Abbaubarkeit. Wenn offen verbrannt, produzieren diese Kunststoffe hohe Luftschadstoffe wie VOC, PAK und PCDD / F (Dioxine). Die Bildung dieser Schadstoffe geht nicht zwangsweise von den Polymeren aus sondern ist eine Ursache des begrenzten Verbrennungsprozesses. Hierfür wurde eine geeignete Technologie entwickelt, die die Kunststoffabfälle in ein heißes Gasgemisch umwandelt und diese anstehend nochmals verbrannt werden und eine enorme Energie freisetzen ohne jegliche Luftverschmutzung. Basierend auf der obigen Hypothese wurden folgende Studienziele anwiesiert:

1. Charakterisieren, quantifizieren und klassifizieren der Abfallfraktionen und Kunststoffkomponenten gemeinsam in vermischten MSW durch manuelle Sortierung
2. Bewertung der Optionen für eine nachhaltige Kunststoff/Abfallwirtschaft insbesondere für die Entwicklungsländer
3. Design, Konstruktion, Test und Optimierung einer geeigneten Technologie, die

die Pyrolyse und den Vergasungsprozess beinhaltet um nicht-PVC-Kunststoffabfall in Energie umzuwandeln

4. Beurteilung der Effizienz der Technologie basierend auf den Betrieb, die Konstruktion, die Menge und Energieanalyse mit sozioökonomischen und ökologischen Bedeutung

Eine integrierte Methodik mit Überprüfung der aktuellen Literatur, Feld- und Laborexperimente mit Analysen der gemischten Abfall- und Kunststoffabfälle wurde verwendet. Darüber hinaus wurde die Pyrolyse-Vergasung Technologie (PGT) an der BTU Cottbus, Deutschland, Lagos in Nigeria und Dschang, in Kamerun konzipiert, konstruiert, gebaut, getestet und optimiert.

Feldstudien mit natürlichen Beobachtung, Interviews, persönliche Gespräche und Besuche bei Entorgungsorganisationen/unternehmen und Deponien wurden in verschiedenen Städten in Nigeria, Benin Republik und Kamerun durchgeführt. Eine ressourcenorientierte manuelle Sortierung unter Verwendung des Resource-Recovery-Scavenging-Ansatz (RESA) simuliert die Integration von Müllsammler-Aktivitäten in die Mülltrennung und wurde an der BTU und Lagos in Nigeria durchgeführt. Wesentliche Ergebnisse sind:

- Charakterisierung, Quantifizierung und Qualifizierung einer trockenen Probe vermischten MSW in Cottbus, Deutschland ergaben große Abfallfraktionen ,in absteigender Reihenfolge, als 23,15% Restmüll, 19,75% Papier und Karton, 17,80% Kunststoffen, 14,63% Textilien und Windeln , 10,06% Speiseresten und 9,55% aus Glas mit insgesamt 33.21% kompostierbar zur Gewinnung von Dünger, 52,2% nutzbar als Einsatzmaterial in der PG-Technologie und 99,81% des gesamten Probe mit einem Material- oder Energierückgewinnungspotenzial. In Lagos, Nigeria ergaben sich Hauptfraktionen von 29% Kunststoffe, 36% Restmüll, 17% Boden / Sand, 7% Papier mit insgesamt 41% nutzbar als Einsatzmaterial in PG-Technologie, 39% kompostierbar, 3% recycelbar (Metall und Glas), während Sand aus dem Boden / Sand-Fraktion für den Bau wiederhergestellt werden können. Ohne das Sand / Erde Gemisch, haben 83% der gesamten Probe des Abfallaufkommens Potenzial zur stofflichen und



energetischen Wiederverwertung.

- Eine entsprechende Technologie, die Prinzipien der Pyrolyse und Vergasung nicht-PVC-Kunststoffabfalls in Energie umzuwandeln wurden so konzipiert, gebaut, getestet und optimiert im Hinblick auf:
  - (i) ein erfolgreiches Funktionieren mit der Umwandlung von durchschnittlich 98,51% des Eingangsinputs wobei 82,78-98,21% der Holzkohle und 96,72-99,27% der Kunststoffs in Energie umgewandelt wurden
  - (ii) Bewertung der sozioökonomischen und ökologischen Auswirkungen bei der Pyrolyse und die Abgas- und Ascherückstandanalyse zeigte keine VOCs, Schwermetalle und Schadstoffen organischer und anorganischer Verbindungen,
  - (iii) die Sicherheit und Risikobewertung der Luftverschmutzung in Innenräumen ist sehr niedrig, da die einzeln gerichtete Strömung der Abgase durch das System basier auf dem natürlichen Luftzug,
  - (iv) Bei der Beurteilung der WTA und WTP gaben 94% der Befragten in Lagos, Nigeria und Porto Novo, Benin an, dass sie bereit sind die Technologie zu akzeptieren und auch für diese etwas zu bezahlen.

Die Bewertung von Optionen für eine nachhaltige Kunststoffabfallbehandlung mit Energierückgewinnung mittels PG-Technologie bietet eine kostengünstige und erschwingliche Wahl für die meisten Entwicklungsländer aufgrund seiner schadstofffreien Arbeitsweise, interner Verwertung der Energie, geringe Kosten und Null Innen- und Außenluftverschmutzungen. Mit der PG-Technologie verbessern lokale Gemeinden ihre "Fähigkeit", sich saubere, effiziente und sichere Energie zum Kochen und Heizen leisten zu können, mit dem Potenzial für die Kombination aus Hitze Strom zu erzeugen. Diese wissenschaftlichen und technologischen Ansatz und das Prinzip können angewendet werden, um Kraftstoff Wirkungsgrad von Motoren und Verbrennungsanlagen zu verbessern.

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## List of Chemical Formulae and Symbols

| Chemical formula/symbol       | Nomenclature                           |
|-------------------------------|--|
| ABS                           | Acrylonitrile Butadiene Styrene        |
| As                            | Arsenic                                |
| C <sub>2</sub> H <sub>6</sub> | Ethane                                 |
| C <sub>3</sub> H <sub>8</sub> | Propane                                |
| CaO                           | Calcium oxide                          |
| Cd                            | Cadmium                                |
| CH <sub>4</sub>               | Methane                                |
| H <sub>x</sub> C <sub>y</sub> | Hydrocarbons                           |
| Cl <sub>2</sub>               | Chlorine                               |
| CO                            | Carbon monoxide                        |
| CO <sub>2</sub>               | Carbon dioxide                         |
| Cr                            | Chromium                               |
| Cu                            | Copper                                 |
| CU <sup>2+</sup>              | Copper (II) ions                       |
| DXN                           | Dioxins                                |
| EPS                           | Emulsion polymers                      |
| Fe <sup>3+</sup>              | Iron(III) ions                         |
| H <sub>2</sub>                | Hydrogen                               |
| H <sub>2</sub> O              | Water                                  |
| HCl                           | Hydrogen chloride or hydrochloric acid |
| HCN                           | Hydrogen cyanide                       |
| HDPE                          | High density polyethylene              |
| Hg                            | Mercury                                |
| LDPE                          | Low Density Polyethylene               |
| LLDPE                         | Linear Low Density Polyethylene        |
| NO                            | Nitrogen (II) oxide                    |
| NO <sub>x</sub>               | Nitrogen oxides                        |
| O <sub>2</sub>                | Oxygen                                 |



|                  |  |
|------------------|--|
| PAH              | Persistent aromatic hydrocarbon            |
| Pb               | Lead                                       |
| Pb <sup>2+</sup> | Lead (ii) ions                             |
| <i>PBT</i>       | Polybutylene Teraphthalate                 |
| <i>PC</i>        | Polycarbonate                              |
| PCB              | Polychlorinated biphenyl                   |
| PCDD             | Polychlorinated dibenzo-dioxins            |
| PCDD/F           | Polybrominated dioxins and furans          |
| PCDF             | Polychlorinated dibenzo-furans             |
| PEF              | Process engineered fuel                    |
| PET              | Polyethylene Teraphthalate                 |
| PP               | <i>Polypropylene</i>                       |
| PS               | Polystyrene                                |
| <i>PU</i>        | Polyurethane                               |
| PVC              | Polyvinylchloride                          |
| RDF              | Refused derived fuel                       |
| SO <sub>2</sub>  | Sulphur dioxide                            |
| SO <sub>x</sub>  | Sulphur oxides                             |
| SVOC             | Semi volatile organic compound             |
| TCLP             | Toxicity characteristic leaching procedure |
| TNT              | Trinitrotoluene                            |
| VOC              | Volatile organic compound                  |
| Zn               | Zinc                                       |
| Zn <sup>2+</sup> | Zinc (II) ions                             |

## List of Acronyms/Abbreviations

| <b>Acronyms/abbreviation</b> | <b>Full expression</b>                    |
|------------------------------|---|
| AHET                         | Appropriate household energy technology   |
| APW                          | Agriculture plastic waste                 |
| ATEX                         | <i>AT</i> mosphères <i>EX</i> plosives    |
| BTU                          | Brandenburg University of Technology      |
| CSA                          | Canadian Standards Association            |
| CV                           | Calorific value                           |
| DNAPL                        | Dense non-aqueous-phase liquid            |
| GC-MS                        | Gas-chromatography-mass spectroscopy      |
| GDP                          | Gross domestic product                    |
| GHG                          | Greenhouse gas                            |
| H/C                          | Hydrogen/Carbon ratio                     |
| HSE                          | Health safety and environment             |
| HW                           | Household waste                           |
| IAP                          | Indoor air pollution                      |
| IPCC                         | Intergovernmental panel on climate change |
| LAWMA                        | Lagos waste management authority          |
| LCA                          | Life cycle assessment                     |
| LNAPL                        | Low density non-aqueous-phase liquid      |
| M/Z                          | Mass/charge ratio                         |
| MDG                          | Millennium development goals              |
| CDM                          | Clean development mechanism               |
| MSW                          | Municipal solid waste                     |
| MWC                          | Municipal waste combustion                |
| NAPL                         | Non-aqueous-phase liquid                  |
| ND                           | Natural draft                             |
| PEF                          | Process engineered fuel                   |
| PG                           | Pyrolysis-gasification                    |
| PGP                          | Pyrolysis-gasification process            |

|      |  |
|------|--|
| PGT  | Pyrolysis-gasification technology          |
| R&D  | Research and development                   |
| RDF  | Refuse derived fuel                        |
| RESA | Resource-recovery scavenging approach      |
| RT   | Retention time                             |
| SEA  | Strategic environmental assessment         |
| SF   | Substitution factor                        |
| SME  | Small and medium sized establishments      |
| SPME | Solid phase micro-extraction               |
| STLS | Simpson transfer loading station           |
| TCLP | Toxicity characteristic leaching procedure |
| TG   | Thermo gravimetric                         |
| UL   | Underwriters Laboratories                  |
| UNEP | United nations environmental program       |
| VHS  | Video home system                          |
| WBT  | Water boiling test                         |
| WEEE | Waste electric electronic equipment        |
| WTA  | Willingness to accept                      |
| WTP  | Willingness to pay                         |

Plastics, Energy and Waste Management Challenges

Chapter One

Research Problem Analysis and Resource Sustainability Issues

1.0 Emerging Issues in the Energy and Environment

According to ‘emerging issues in our environment’, scientists are concerned that plastics debris in the ocean can transport toxic substances which may end up in the food chain causing potential harm to ecosystem and human health (UNEP 2011). The Yearbook emphasizes the need to halt loss of forest biodiversity and deforestation to enhance climate change mitigation and adaptation.

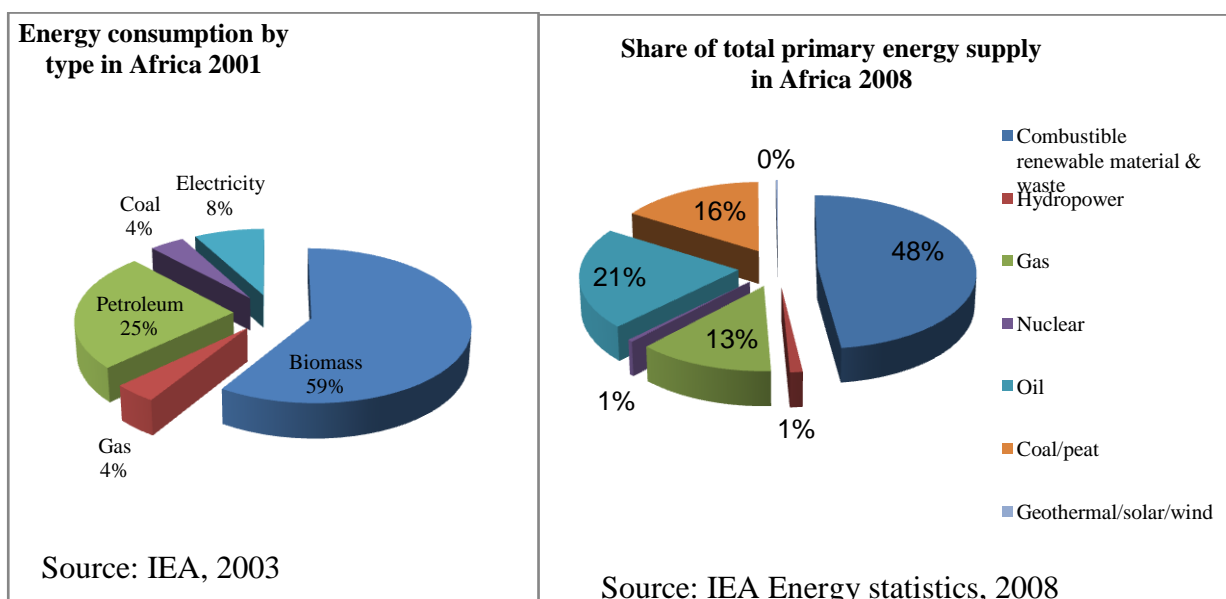


Figure 1.1 Domestic energy sources in sub-Saharan Africa in 1994

Hence developing and vulgarising new technologies which enhance investment in natural capital (forest) based on alternative energy utilisation and resource use efficiency is essential. Recovering renewable energy from combustible waste especially plastics (Table 1.1) reduces reliance on wood which is a major cause of deforestation, in- and out- door pollution, land degradation, groundwater depletion and desertification. Cameroon like most developing countries of sub-Saharan Africa possess a vast unexploited renewable energy potential which includes solar, wind, hydropower and waste rich in combustible organic matter.

Table 1.1 Waste collection typologies by GDP per capita

| Particulars   | Income of countries   |   |  | Remarks  |
|---|---|---|--|--|
|   | Low   | Middle  | High   |  |
| GDP in \$/Capita/year                                   | < \$5,000   | \$5,000-15,000  | \$5,000-15000                                      | Increase development raises waste production rates requiring strategies & statutory framework that use effective statistics as management decision support systems |
| Average consumption of paper/cardboard (kg/capita/year) | 20  | 20-70   | 130-300  |  |
| Municipal waste (kg/capita/year)                        | 150-250   | 250-550   | 350-750  |  |
| Formal collection rate of Municipal waste               | <70%  | 70-95%  | >95%   | Influences cost -effective management of waste services  |
| Putrescibles (weight %)                                 | 50-80   | 20-65   | 20-40  | Compostable for manure with biogas collection or incinerated for energy production   |
| Paper and cardboard                                     | 4-15  | 15-40   | 15-50  |  |
| <b>Plastics</b>   | <b>5-12</b>   | <b>7-15</b>   | <b>10-15</b>                                       | <b>Incinerate, pyrolyse or gasified releasing energy</b>   |
| Metals  | 1-5   | 1-5   | 5-8  | Recycle at 100% or to secondary materials  |
| Glass   | 1-5   | 1-5   | 5-8  |  |
| Wetness (%)   | 50-80   | 40-60   | 20-30  | Evaporate to atmosphere  |
| Waste treatment   | >50% uncontrolled landfills dumping with 15% informal recycling | >90% landfilled with selective collection & recycling | Selective collection, incineration & >20% recycled | Low income countries need to take advantage of the opportunities, benefits and incentives for waste recycling  |

Source: Adapted from UNEP 2011

Although some of these renewable energy sources are currently being utilised, their proliferation is yet very low. This is due to the high installation cost including production, transmission and distribution challenges involved. However, the percentage reduction of biomass use from 59% (2001) to 48% (2008) indicates a shift towards other alternatives energy sources given the increasing population of Africa (Fig. 1.1).

## 1.2 Ensuring Environmental and Energy Sustainability

Achieving energy sustainability is fundamental to poverty alleviation, environmental protection and improved human welfare. Effective waste management is essential to sustainable natural resource usage. Improving livelihoods requires free access to

energy, food, water, land and resource reliance economic activities (fishing, forestry and farming). However, energy production forms the core hindrance to achieving significant progress in millennium development goals (MDGs) that ensure climate change mitigation and adaptation.

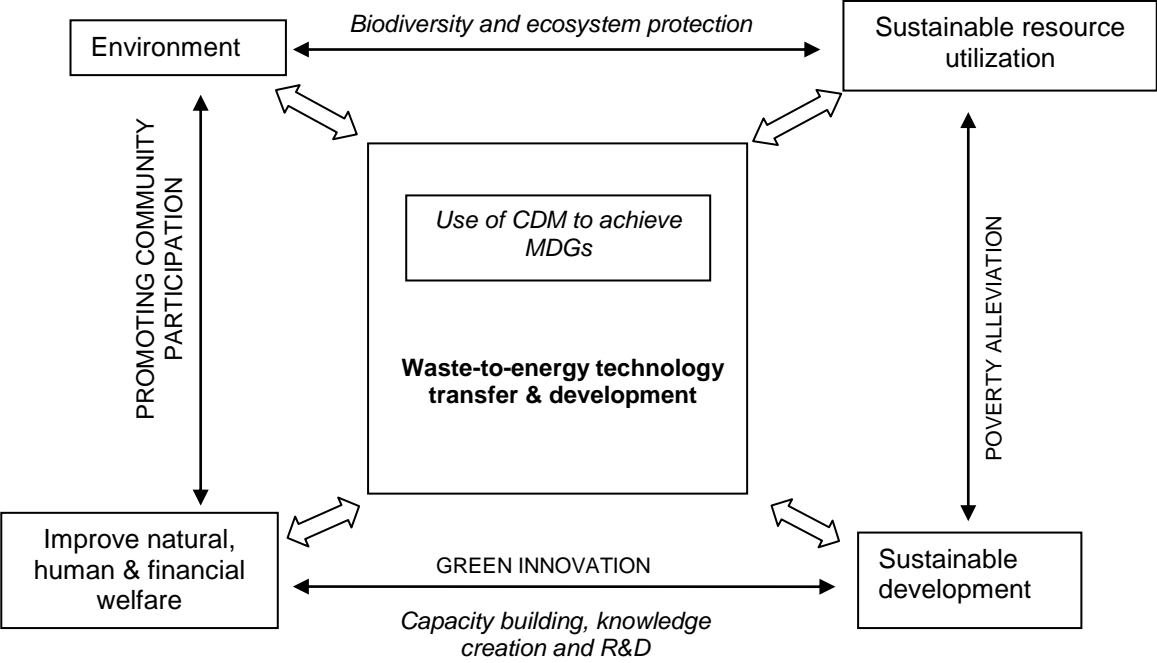


Figure 1.2 Use of technology transfer and development to achieve MDGs

Hence the production, consumption and distribution of energy from waste influence the ability to eradicate poverty while enhancing human welfare. Figure 1.2 illustrates the role of energy in achieving environmental protection, MDGs and climate change mitigation and adaptation. The interplay (double arrows) of anthropogenic factors (improvement of health, welfare and poverty alleviation) with application of waste-to-energy technology (green innovation practices) to achieve MDGs leads sustainable development minimum environmental impacts.

**1.3 Tackling the Energy and Climate Change Problem**

An integrated approach to waste management involves treatment, sorting, marketing and using various waste streams to achieve several socioeconomic benefits. Developing a new technology that uses high calorific waste fraction to produce energy promotes the achievement of MDGs and human welfare services such as:

- Reducing poverty and hunger through use of compost to improve crop yields, creating jobs in waste sector which increases income and reducing energy cost

- Promoting gender equality and women empowerment through economic incentives resulting from marketing of recovered materials from waste
- Recovering waste plastics for energy production eliminates mosquito breeding habitats (standing waters) reducing malaria, child mortality and air pollution
- Influencing environmental sustainability policy and community behaviour towards improving waste management services (Forbid et al., 2011b).

Developing a technology that transforms waste to energy induces and enhances a bottom-up approach to waste management. This approach is driven by economic benefits since related waste components will be targeted for recovery by users or scavengers collecting to sale. Consequently, it motivates public participation in material recovery for alternative energy production and marketing (Forbid, 2010).

#### 1.4 Energy Sources, Demand and Consumption

Reliance on particular energy source depends on availability and accessibility of technology, quantity of energy obtainable and fuel source. Various fuels use different technologies to produce various energy forms e.g. heat, light and electricity. Fuel affordability and availability determines user fidelity of energy conversion technologies. Hence the regular use of wood and charcoal in most developing countries especially in Africa is influenced by these factors. Domestic energy demand in sub-Saharan Africa in 1994 shows 63% and 9% dependence on wood and charcoal respectively.

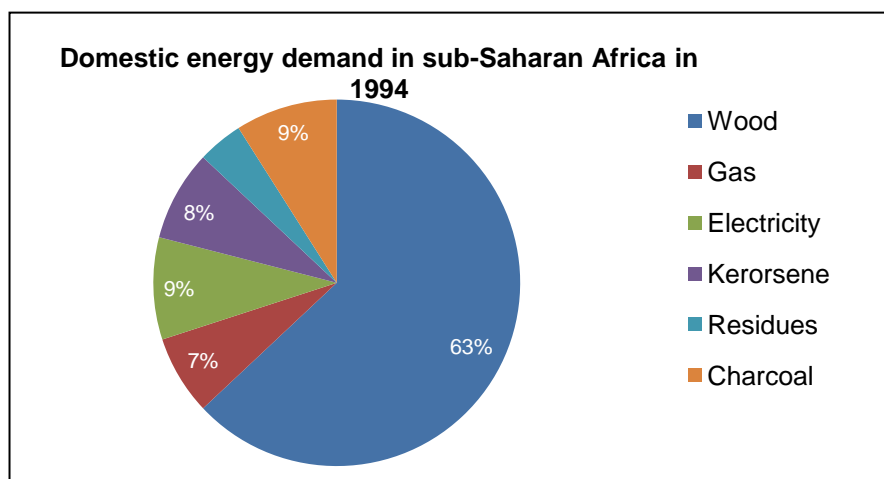


Figure 1.3 Domestic energy demands in sub-Saharan Africa in 1994

Population growth increases waste production with a corresponding demand and consumption for goods, fuel and energy (Fig. 1.3). The recovery of combustible materials from waste for energy production minimizes the dependence on wood reducing deforestation. Hence, developing a technology that transforms waste to energy when fossil fuel demand and prices are rising offers multiple benefits (Fig. 1.4).

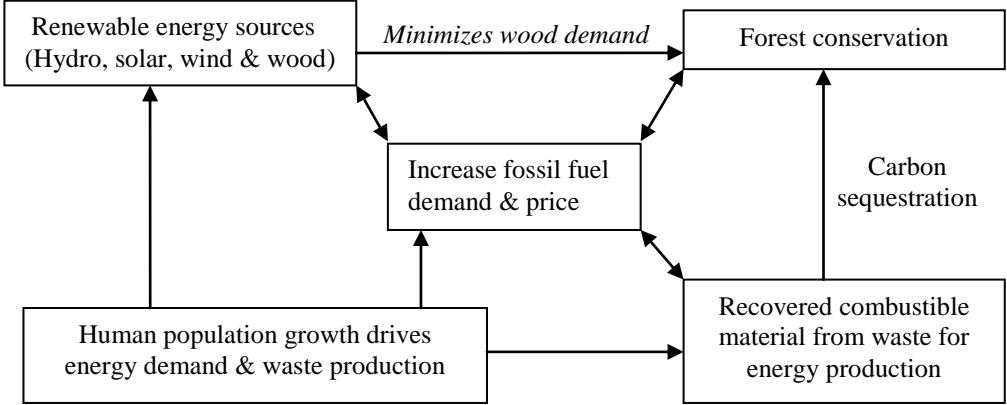


Figure 1.4 Modelling energy sources, demand and human impact interrelationships

**1.5 Energy from Biodegradable Organic and Plastic Waste**

Eco-living generates large amounts of organic waste which when composted (aerobic) or anaerobically to produce biogas (fuel) and compost (bio-fertilizer). However, the increase use of plastics packaging has increased composition, complexity and quantity of the waste plastic fraction in municipal solid waste (MSW). Plastics’ high caloric value, increasing usage and availability makes it a sustainable energy source.

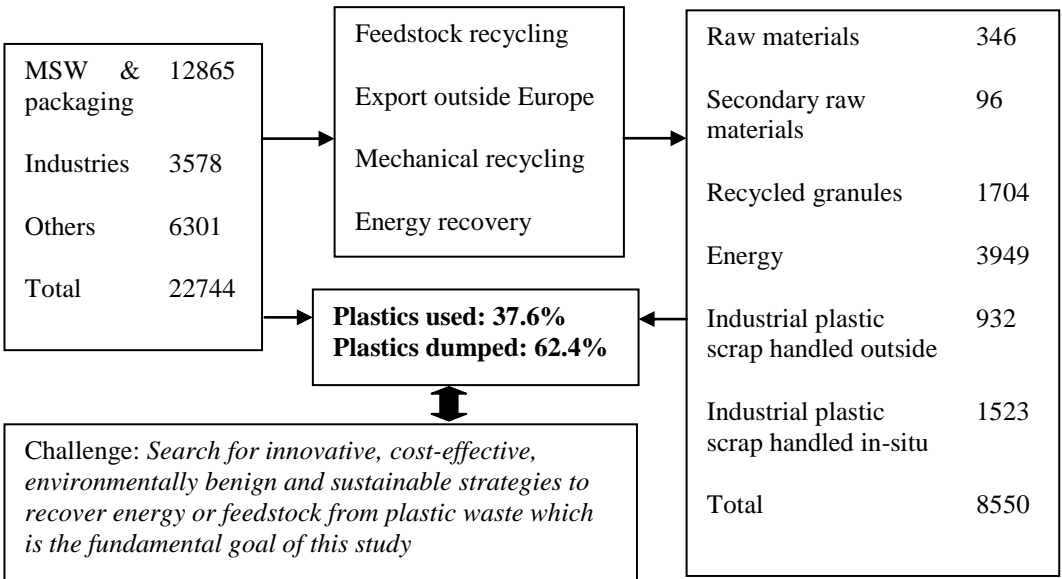


Figure 1.5 Need identification of current plastic waste disposal challenges



Although developed countries like Germany employ various reuse and recycling methods (feedstock recycling, mechanical recycling and energy recovery) to achieve 37.6% of waste plastic used, most of the 62.4% of waste plastic is dumped or exported out of Europe (Fig. 1.5). Hence, developing a cost-effective, safe and environmentally-friendly technology for transforming plastic waste into energy seeks to solve a crucial global energy and waste management problem.

### 1.6 Plastic Waste Disposal as a Global Problem

The high calorific value of plastics underscores the need for an alternative energy recovery technology that is affordable, efficient, safe and user-friendly. Little attention has been paid to using plastic waste as an energy source especially in the developing countries which lack technical know-how and appropriate plastic-to-fuel technologies.

Reasons for such lack of attention to the energy value of plastic are:

- Plastics produces poisonous gases, odour and smoke when burned directly
- Waste plastic recycling, feedstock and secondary material production is expensive and less cost-effective
- Secondary materials from waste plastics has low quality and sometimes is more expensive than virgin raw materials



Figure 1.6 Disposal of plastic waste as a global menace

- Most developing countries are plastic end-users not producers
- Plastics are just too easy to throw away due to their low cost and light weight
- Plastics are non-biodegradable and have low density making them easy to be carried away by wind and surface moving waters (Fig. 1.6)

### 1.6.1 PG Technology as Multiple Problem-solution Package

Developing a waste-to-energy technology guarantees rational resource utilization as basis for sustainable development. Although this technology can be use for both biodegradable and non-biodegradable (plastics) waste, the later is preferred due to:

1. Plastics are functional, highly versatile leading to increase usage but have low cost-effective recyclability and are non-biodegradable
2. Disposal by dumping or land filling offers a global problem with major adverse ecological impacts due photo-degradation, low compressibility, resilient surfaces, extremely long rotting time and forming of cavities within air inclusion in landfills etc (Angyal et al., 2007; Biniecka et al., 2005; Blasi, 1997; Boer et al., 2005)
3. High calorific value range of 5-10 times that of wood depending on type and moisture content

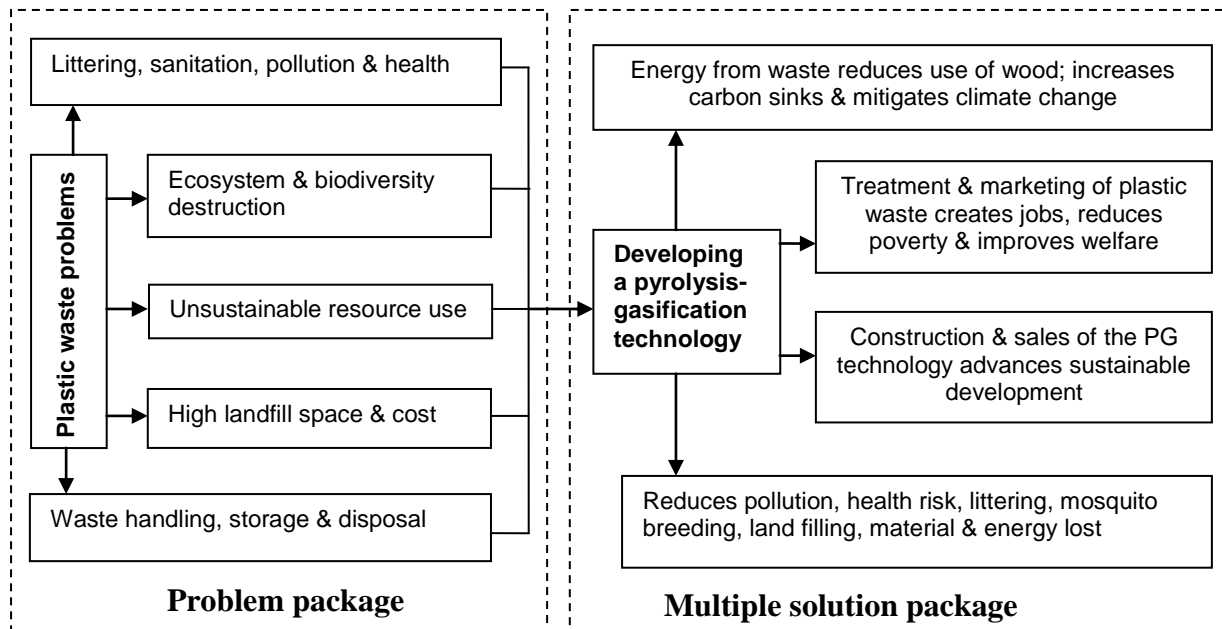


Figure 1.7 Major problems solved by thermal recycling of plastic waste

1. Plastics production and utilization as raw materials for various industrial products and packaging is increasing leading to an estimated annual consumption of about 39.1 million tonnes in Western Europe (Starreveld & Vanierland, 1994; Bhandare et al., 1997; Kasakura et al., 1999; Aguado et al., 2007).

This situation causes an ever-growing economic, household, community and global disposal problem in both industrialised and developing countries (Fig. 1.7). Most of plastic waste packaging accompanies finished goods from manufacturers to end-users (Ferrara & Missios, 2005; Zielinski et al., 2000). Hence next chapter evaluates efforts and state-of-the-art technologies developed to solve plastic waste disposal problems.

## Chapter Two

### Tackling the Plastics, Energy and Waste Management Dilemma

#### 2.0 Use of Plastic Materials in Current Economic System

Plastics' role in reducing environmental loading, preservation of foods under varied temperature conditions and transport cost minimization is highly invaluable. Yet, increase use of plastics, recycling and management has led to its dominance in the environment as non-biodegradable waste with enormous negative impacts (Isio & Xanthos, 2006; Hernandez et al., 2000; Nasakura et al., 1999; Lardinois & Klundert, 1995; Hamerton et al., 2003). Hence, modelling plastic production, usage and effective disposal requires favourable legislations and state-of-the-art technologies that endorse sustainability (Fig. 2.1).

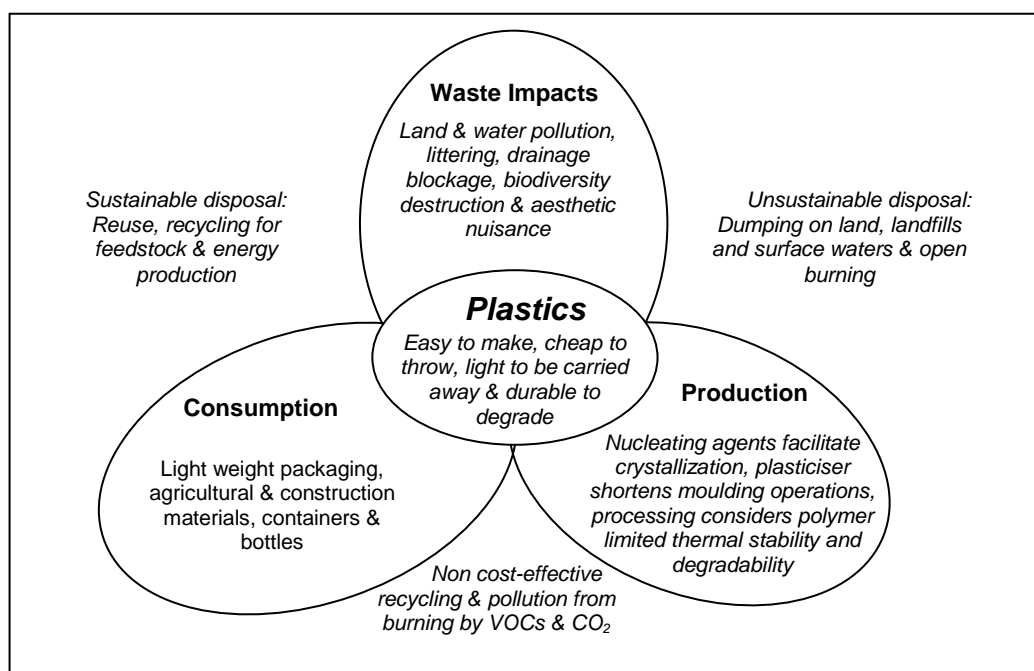


Figure 2.1 Modelling plastic production, usage and disposal of waste

However, increasingly stringent environmental legislations set higher standards that promote the application of novel mechanical and feedstock recycling technologies. Such currently applicable thermal recycling methods include pyrolysis, catalytic conversion, depolymerisation and gasification to transform plastic waste to hydrocarbon fuel products or chemical feed stocks.

## **2.1 Tackling Indoor and Outdoor Air Pollution**

Many people around the world lack effective cooking technologies that are affordable, energy efficient and emissions free. The PG technology provides an outlet that channels exhaust gases through a chimney into the atmosphere. Multiple air inlets occur to enhance air mixing while a single exhaust gas outlet provides a single direct out-flow of air. The exhaust gas outlet or chimney presents a threshold bottle-neck control ensuring the combustion chamber always has excess oxygen. The successful application of the research results creates a basis for:

- Enhancing legislative review and reform in the energy and waste management sectors
- Promoting capacity building for individuals and institutions within pilot projects
- Creating technology and evaluating distribution and operation potentials in laboratory and field studies for providing cheap, sustainable and clean energy to millions of poor rural and city dwellers
- Providing access to cleaner energy resources while promoting economic development, health and safety

## **2.2 Millennium Development Goal Relevance**

Solving the MSW and plastic waste management issues challenging developing countries is fundamental to achieving the Millennium development goals (MDGs). MDGs related benefits of the use of plastic waste as an alternative energy source are:

- Reduced dependence on wood and fossil including labour, cost, time and risk involved in wood fetching
- Curbing deforestation with resulting desertification, forest biodiversity loss and prevention of land degradation
- Conserving forest enhances water balance, biodiversity protection, food security and carbon dioxide sequestration for climate change mitigation
- Construction and marketing of the technology including sales of recovered waste plastics creates employment for constructors, waste collectors and distributors boosting the economy and alleviating poverty. Such economic activities lead to empowering women who can afford to finance the education of their children and other basic needs (Forbid et al., 2010; Fomba et al., 2011).

- Improving environmental policy would improve the social and economic situation of developing countries while ensuring sustainable resource utilization, good health, hygiene and sanitation (Nagel, 2002; Petts & Eduljee, 1994)

Sorting plastics makes recovery of other components (metals, glass and paper) and composting of the 60-80% organic waste for bio-fertilizer production easier. Such material and energy recovery saves landfill space while reducing pollution and greenhouse gas emissions.

### 2.3 Causes and Impacts of Plastic Waste Pollution

Plastics are easy and cheap to make and last a long time. These properties hone its usefulness and underpin the huge environmental and pollution problem linked to their disposal. Plastics are readily discarded due to low cost and low density yet their persistence in the environment causes land pollution and blockages in drainage lines causing floods in some cities (Williams & Williams, 1997, Forbid et al., 2011d).

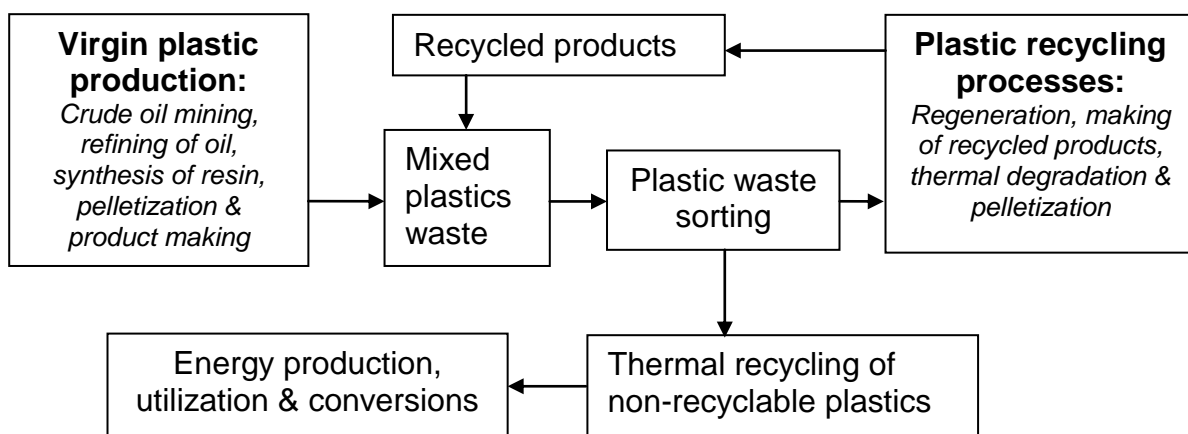


Figure 2.2 Optimal lifecycle-based plastic waste management model

Other impacts of plastic waste pollution include:

- Plastic components eaten by animals, birds and fishes causing intestinal blockages, digestive and starvation crisis resulting in death
- Oceans' pollution is on the rise with over 90% of articles and waste at sea beaches containing post consumer plastics
- Plastic waste causes aesthetic nuisance in cities, presents risk to biodiversity destruction resulting from direct entanglement and trapping of plant roots.

The potential environmental impacts from plastics are categorised under global warming, acidification, eutrophication and photochemical ozone creation (Bos et al., 2007). Limitations to plastic recycling include:

- Recycled plastics have lower quality compared to virgin materials and possess a low economic profile due to high recycling cost
- Although, the application of the substitution factor (SF) has improved the cost effectiveness of plastic recycling to about 10%, this is still below expected economic incentive level
- Thermal recycling of non-recyclable waste plastics offers the most attractive and cost effective option (Noda et al., 2001; Huang & Tang, 2007; Williams, 1998).

Plastics are very stable at normal atmospheric temperature, energy rich and long lasting materials in the environment due to their composition, nature and source (Lund, 2001). Optimal lifecycle-based waste plastic management should prioritise the recycling closed loop with rest non-recyclable plastics thermally converted to energy (Fig. 2.2). Recycling by thermal treatment resulting in chemical feedstock using pyrolysis, hydrogenation, thermal or catalytic cracking, gasification and bioconversion (Hajekova et al., 2007; Forbid et al., 2011c) are potential options for plastic waste disposal.

## 2.4 Drive for Thermal Recycling of Plastic Waste

Table 2.1 Major plastic waste sources, quantities and composition

| Sector                       | Annual tonnage t/a   | Main materials  | Major products   |
|------------------------------|--|---|--|
| Farming                      | 48000<br>(1.6%)  | PE sheets   | Fences, fixation of river banks, horse-boxes and fish boxes  |
| Building & construction      | 66000<br>(2.2%)  | PVC, PP, acrylic polymers   | Waste pipes, drains, sheets, bed plates, curbstones, limbering and insulating materials  |
| End of Life cars & transport | 204000<br>(6.8%)   | PE, PP, PA, PVC, PUR, polyester resins, ABS, PS, Duroplasts, PMMA | Seats, under sealant dumper, pallets, noise barriers, outside mirrors, heating fuel containers, side rails, brakes, pads, radiators, paneling motor electrics, landing stages, insulation and rear lamps |
| Commerce & trade             | <b>567000<br/>(18.9%)</b>  | <b>PE sheets</b>  | <b>Bins, bags and coverings (most common in MSW)</b>   |
| Domestic & garden waste      | <b>2115000<br/>(70.5%)</b>   | <b>PE, PP, PS</b>   | <b>Flower pots, benches, sand boxes and composters</b>   |
| Conclusion                   | <b>Plastics found in MSW: PE, PP, PS, PVC (PVC is not very common)</b> |   |  |

Source: Data adapted from Hamerton, 2003

The main sources of plastic waste in MSW are identified in table 2.1. Identified principal plastic components in MSW include polyethylene (PE), polyvinyl chloride (PVC),

polypropylene (PP) and polystyrene (PS), which form about 70% of total waste plastics (Vesilind et al., 2002; Vollrath et al., 1992; Williams & Williams, 1997). However, in most developing countries due to lack of economic potentials and technological expertise to built incineration plants and install a structured waste management system, disposal is mainly by dumping, burning and land filling (Forbid et al., 2011a).

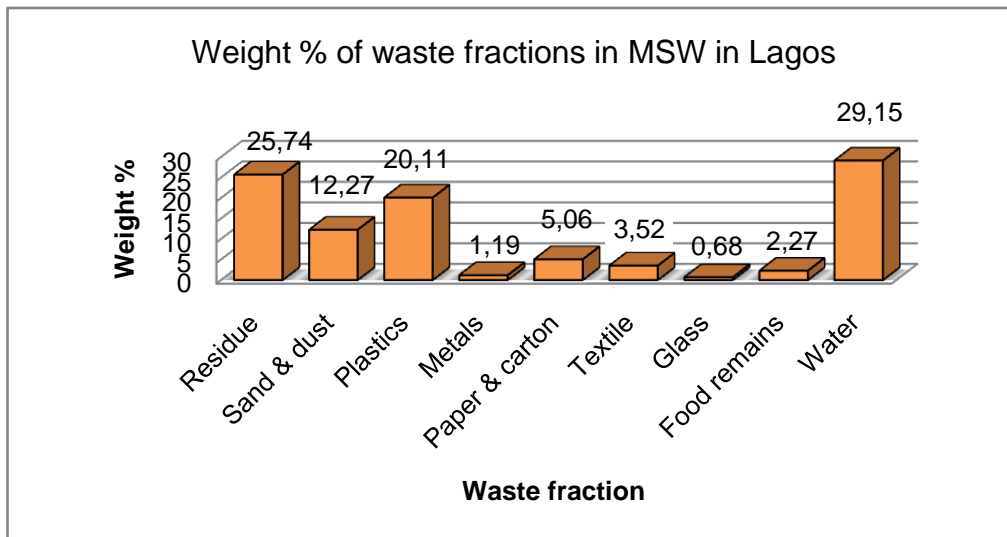


Figure 2.3 Weight % of major waste fractions in MSW in Lagos, Nigeria

In Cameroon, waste plastics form about 39% of non-biodegradable MSW (Achankeng, 2003), which is generally burned in open dumps, deposited in water bodies and storm-drainage channels, along streets or spread in surroundings of waste dumps. In Lagos-Nigeria, a waste analysis gave a plastic fraction of 21.11% (Fig. 2.3).

## 2.5 Incentive for Developing New Technology

Figure 2.4 shows a comparison of current technologies vis-à-vis the PG technology for waste plastics recycling. It identifies and compares the advantages and limitations linked to current pyrolysis and gasification technologies for transforming plastic waste to fuels and chemical feed stocks (Wong & Broadbelt, 2001; Zia et al., 2006). Studies on modern waste disposal technologies and challenges of applying them in developing countries prove that energy recovery from plastic waste has been given little attention despite the high calorific value (Post & Haenen, 2007; Guendehou et al., 2006; Jun'ichi & Tomohiro, 2006).



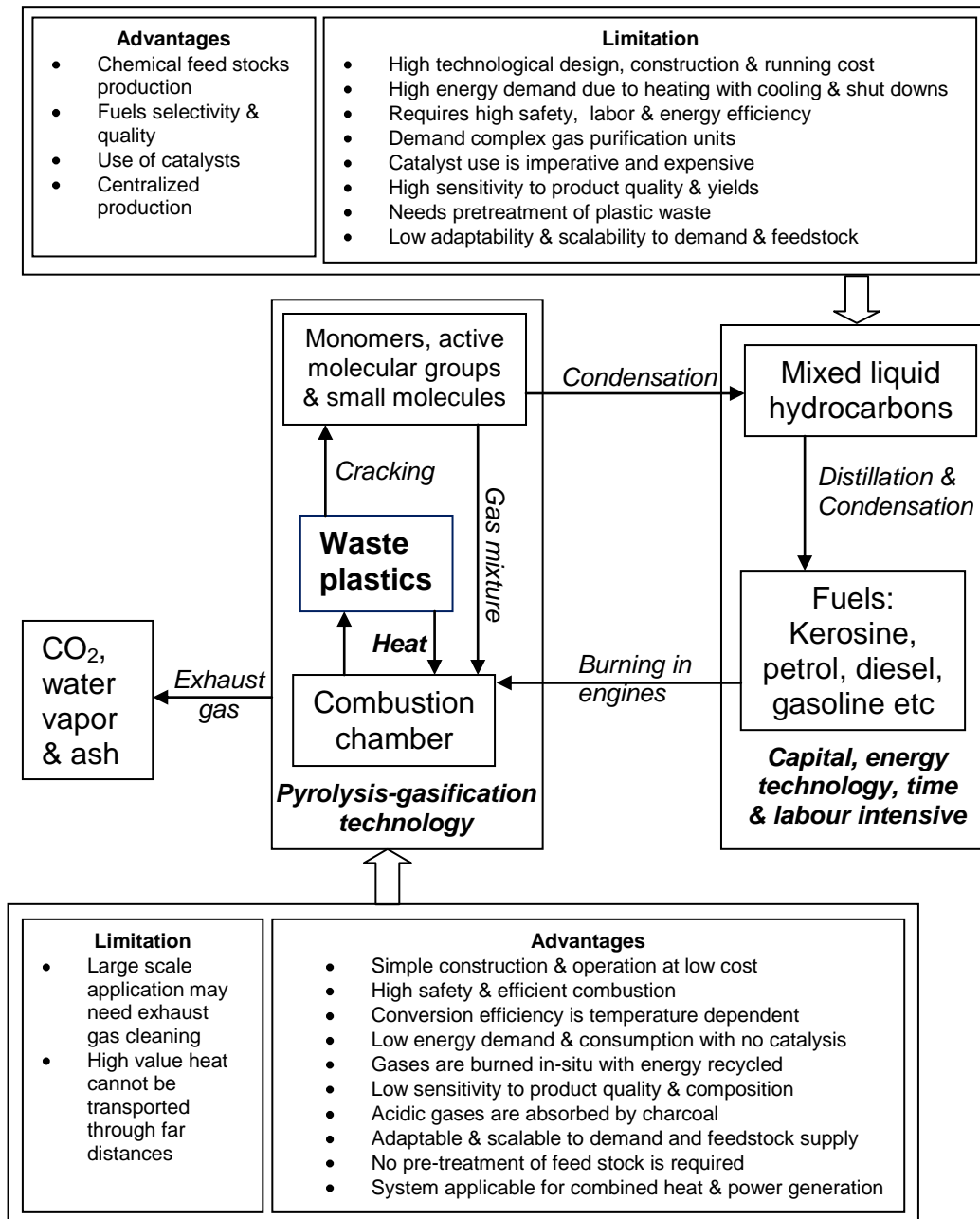


Figure 2.4 Comparing current energy-based plastic waste recycling technologies

### 2.5.1 The Fundamental Concept of the PG Technology

Most waste plastics recycling processes produce secondary raw materials or chemicals used as fuels. According to Ferrara (2005), thermal recycling is virtually applicable to any kind of plastics regardless of the type of polymer, fillers and additives incorporated. However, to prevent pollution effects from mixed MSW plastics, there is need for basic sorting of plastics with potentials to produce acidic gases e.g. PVC. Zhang et al. (2006) supports pre-treatment concluding that collecting, sorting and classifying plastic waste

influences the characteristics of liquids and gaseous products formed. Products formed depend on the chemical nature, carbon number and structure of the plastic types including type and economics of the technology applied (Lee, 2006).

With optimum pyrolysis conditions and liquefaction at moderate temperature and pressure, about 80% of the original feedstock is converted into gaseous products e.g.  $\text{CH}_4$ ,  $\text{C}_2\text{H}_6$ ,  $\text{C}_3\text{H}_8$ , alkenes and aromatics compounds (Williams & Staney, 2007). Since pyrolysis gases from plastics are highly inflammable with relative toxicity depending on pyrolysis temperature, catalyst, reaction lapse time, place, system temperature profile, fire type, organic impurities, heating and air-flow rates, attention should be paid to safety considerations (Nakao et al., 2005; Pfeffer, 1992; Bhandare et al., 1997; Pinto et al., 1999; Zielinski et al., 2000). Although according to the 1996 IPCC guidelines,  $\text{CO}_2$  from plastics incineration or open burning form part of the national  $\text{CO}_2$  emission (Guendehou et al., 2006), the efficient recovery and conversion of waste plastics to energy saving the forest compared to dumping and open burning offers a comparative advantage.

## 2.6 Motivations for the Study



Figure 2.5 Consumer waste plastics form a complex mixture

Although plastic waste is produced by manufacturers and consumers of products, this study focuses on consumer plastic waste from MSW. Obtaining plastics components from MSW in a reusable form and quality is highly doubtful implying that recovered high calorific mixed plastics are most appropriate for thermal recycling (Fig. 2.5).

Recycling reduces waste volumes and contributes to energy and resource conservation. Thermal or tertiary recycling (hydrolysis, pyrolysis or gasification) is a technique that uses heat to decompose plastics in the absence or limited amount of oxygen. This process applies to mixed plastics from MSW which cannot be cost-effectively recycled (Noda et al., 2001). The success of this technique is supported by the economic and energy feasibility (Fig. 2.6) resulting from:

- 1) Recuperating and sorting of plastics generating income and creating jobs
- 2) Thermal conversion is efficient without pollution
- 3) Residue treatment, waste dumping or landfill costs are minimized
- 4) Revenue is generated from marketing secondary materials and energy
- 5) Mitigating and adapting to climate change reduces flood risk and desertification

However, depending on the source, type and quality of the waste plastics, the economic benefits may vary. In addition, markets for certain recycled plastics are only available at rates of 10-15% of plastics recycled due to their inferior quality and recycling cost compared to virgin polymers (Williams & Williams, 1997).

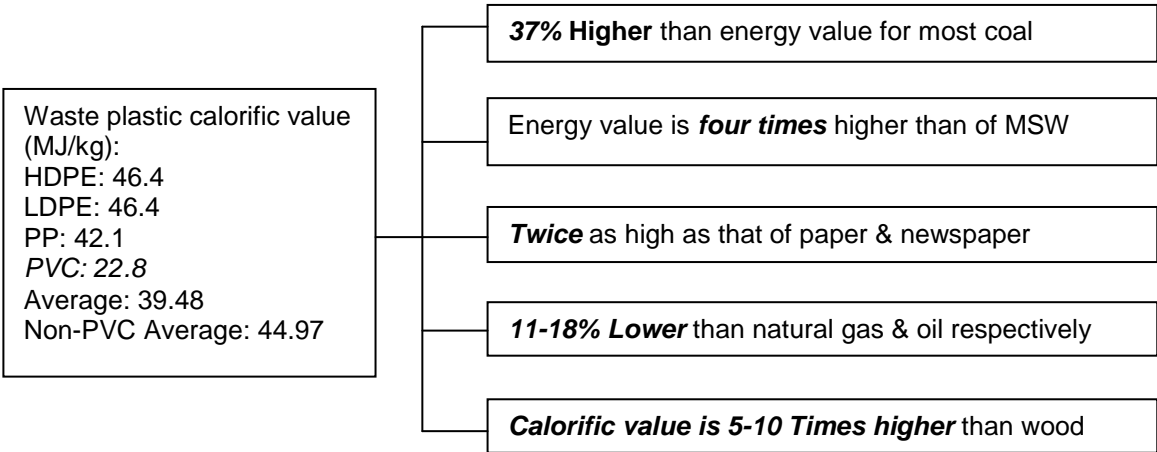


Figure 2.6 Facts about mixed plastic waste energy value

After reviewing literature on modern waste disposal technologies and the challenges of applying them in developing countries, energy recovery from plastic waste has been given little or no attention despite its high calorific value.

## 2.6.1 Forest, Wildlife and Biodiversity Conservation and Carbon Sequestration

Deforestation due to fuel wood demand causes a plethora of socio-economic problems in low income communities which depend on the forest for survival (Tsi et al., 2006). According to Foley et al. (2002) Niamey (capital of Niger) with a population of 800,000 inhabitants is estimated to consume 210,000tonnes of fuel wood annually. Considering a per capita waste production of 0.5kg/day (average for most African cities), estimated total waste generated annually is 146,000tonnes.

Table 2.2 shows the analysis of expected waste plastic weight; energy recovered and landfill space conserved. MSW is often mixed with small quantities of PVC and other waste plastics causing severe management problems due to production of HCl during combustion. However, PVC can be dechlorinated at 633K to recover for neutralisation the HCl to about 99.9wt% or separately burned using the Parr combustion technique (Bockhorn et al., 1999; Lee, 2006). The product has calorific value of 44.000KJ/kg and can be pyrolyse to a non-polluting and highly calorific fuel.

Table 2.2 Analysis of expected gains from energy recovery from plastic waste

| Material                 | CV (MJ/kg) | Weight /tonnes | Energy expected (MJ) | Landfill space saved | Wood saved        | Remarks   |
|--------------------------|------------|----------------|----------------------|----------------------|-------------------|---|
| Non-PVC plastics (12.8%) | 45.03      | 18688          | 841520640 (25.2%)    | 24917.33 (12.8%)     | 52925.83 (25.2%)  | Transport & labour cost reduction, reduced deforestation, resource protection etc |
|                          |            | 30820.6        | 1387851618 (41.56%)  | 41094.13 (21.11%)    | 87286.26 (41.56%) |   |
| Dry wood                 | 15.9       | 210000         | 3339M.               | NA                   | NA                |   |

## 2.7 Aim and Objectives of Study

The aim of this study is to develop an appropriate self-sustained technology that transforms plastic and/or organic waste using pyrolysis and gasification processes to a hot inflammable gaseous mixture which is burned in-situ in a safe and environmentally friendly manner to produce heat energy. Major objectives attained include:

1. Characterize, quantify and classify plastic components and waste fractions common in commingled MSW by manual sorting adapted to developing countries' realities
2. Evaluate options for sustainable plastic waste management targeting achievement of millennium development goals

3. Design, construct, test and optimize an appropriate technology that applies pyrolysis and gasification processes to convert non-PVC plastic waste to energy
4. Evaluate related socioeconomic, technical and environmental impacts of the PG technology in efficient energy production and utilization

## 2.8 Significance of Study

A waste-to-energy process and technology is valorised as an alternative sustainable energy source. This contributes significantly in solving the socioeconomic, health and environmental problems linked to waste disposal in general and plastic waste management in particular. Employing facts on plastic and its waste within a preventive problem-solving approach:

- Emphasizes incentive-driven community participation for plastic waste recovery, sorting and basic treatment leading to improved material quality and marketing
- Advances scientific and technological knowledge in energy recovery from high calorific value waste while protecting the environment, resources and forest

## 2.9 Description of the Case Studies

This research was conducted across international boundaries with most activities conducted in Germany as developed country (in Europe), and Nigeria, Cameroon and Benin (in Africa) republic as developing countries (Fig. 2.7). The effectiveness in waste management services in all these case studies vary significantly.

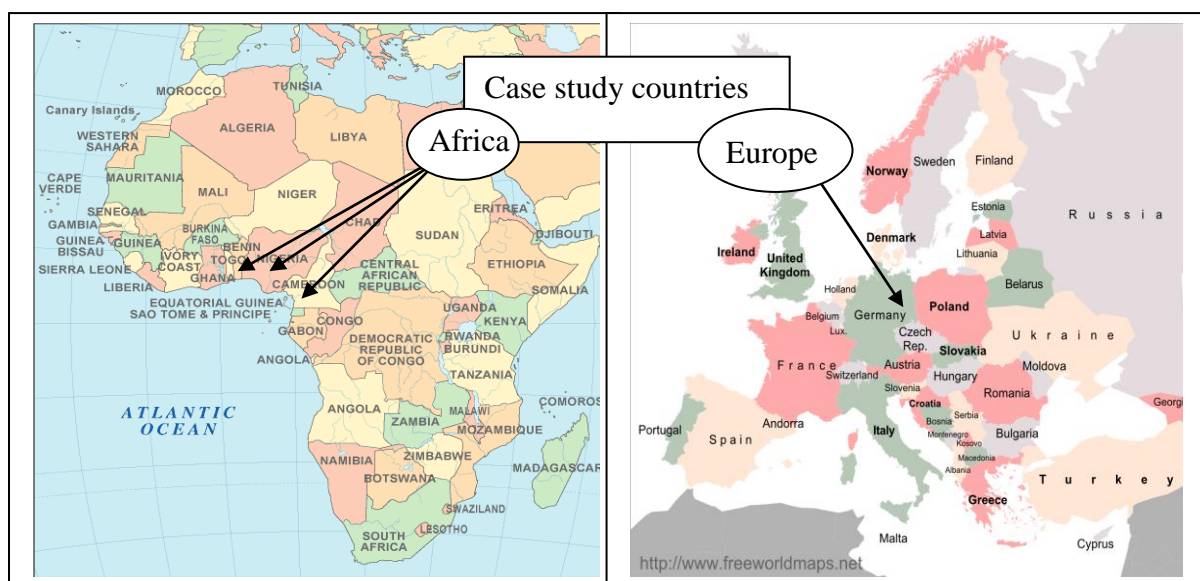


Figure 2.6 Case studies: Germany, Cameroon, Nigeria and Benin Republic

In addition, Nigeria, Benin, Cameroon and Germany are countries with significant variation in socioeconomic, geophysical, climatic and political conditions including population, culture and settlement types. These set of complex factors influence production and consumption of goods and services with consequences on waste generation, characteristics, composition and management.

This thesis considers the complex diversity while carefully blending the field experiences and natural observation of the author. The analysis of issues from a multidisciplinary perspective culminates in the design of an adapted resource-recovery approach to sustainable waste management. This approach emphasises exploitation of opportunities, constraints and incentives for effective waste management and minimization with alternative energy and secondary material recovery (Cheremisinoff, 2003; Grover et al., 2000).

## Chapter Three

### Theoretical Basis of Plastic Waste Pyrolysis and Gasification

#### 3.0 Renewable Energy Potentials and Exploitation

Various exploitable forms of renewable energies exist in most developing countries of Africa contributing significantly to the energy-mix (Fig. 3.1). The production and utilization of renewable energy accompanied by energy-use minimization are fundamental to combating climate change impacts and achieving sustainable development.

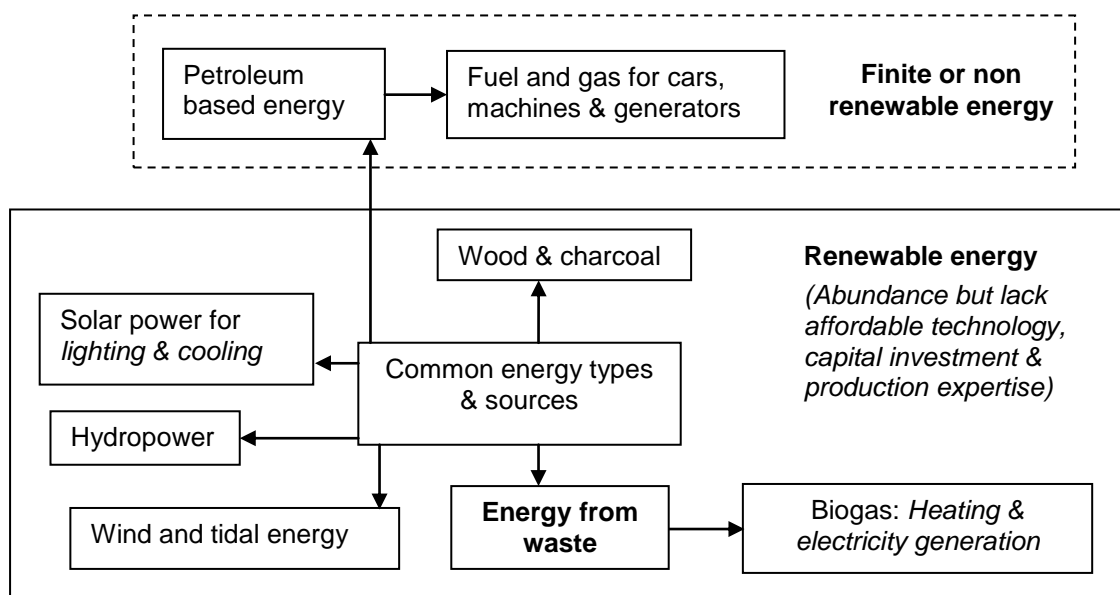


Figure 3.1 Sources and valorization of renewable energy resources

Although renewable and non-renewable energy forms are exploited in various communities, non-biomass renewable energy application is still very limited. Such limited exploitation is attributed to lack of economic prowess, appropriate technology and know-how. Relevant education, awareness and problem-solving research is lacking in various energy fields. This study initiates ongoing research in the field of renewable energy with emphasis on development of affordable waste-to-energy technologies.

#### 3.1 Optimal Utilization of Biomass for Energy Production

The major energy source for cooking and heating in most African countries is biomass combustion mainly obtained from the forest. The wood and charcoal (biomass) are renewable energy sources having multiple applications (Fig. 3.2).



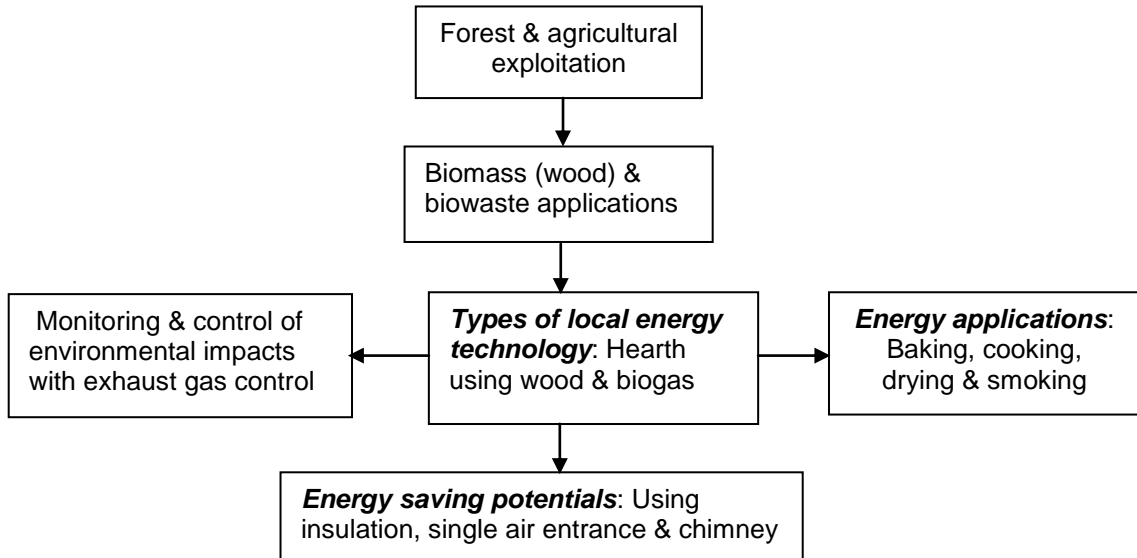


Figure 3.2 Valorisation and utilization of biomass for energy production



Figure 3.3 Locally made stoves common in African countries

Various biomass technologies have been adapted to various fuel sources but with limited efficient energy use and pollution control. Some of these improved biomass technologies, ovens, dryers and heaters constructed with local materials possess good insulation properties.

Developing a new alternative energy production technology to be accepted by wood dependent and environmentally non-sensitive culture required very strong incentives. The locally made energy technologies (Figure 3.3) lack energy-use efficiency. Improving



energy performance and developing alternative waste-to-energy technologies will reduce deforestation significantly.

### **3.2 Pyrolysis-gasification of Plastic Waste**

Application of pyrolysis and gasification for energy production and recovery has been used in industries with significant success though development is still ongoing. Although plastic and biomass pyrolysis and gasification are possible, this study focuses on the plastic waste. Hot pyrolysis-synthesis gas mixture produced is burned in-situ with the energy released, recycled internally to keep the process self-sustainable. Major strengths of the PG process include:

- 1) Tolerance to untreated feedstock, moisture and contamination
- 2) High process efficiency, availability and reliability integrated in a robustly designed technology that is scalable, replicable and adaptable to demand
- 3) Full automation operation is possible with low maintenance cost
- 4) The hot gas produced could be used to power engines and gas turbines without expensive cleaning within combined heat power generation and cooling
- 5) Technology is adapted to pro-poor communities for simultaneously solving the plastic waste disposal and energy problem
- 6) System is safe with affordable low initial investment and running cost

Recovery of secondary raw materials or energy will reduce significantly the amount of waste land filled. Combining legal and economic policies with relevant technologies can drive economic viability within a competitive market for secondary materials from waste.

### **3.3 Using PG Technology with Polyvinyl Chloride (PVC)**

Understanding the sources of PVC helps to determine collections curb centres collection and orientation of effort during sorting. PVC has varied applications though occurring in limited quantities in MSW. Eliminating chlorinated plastics mainly PVC as a major source of chlorine reduces HCl and chances for dioxin formation. Figure 3.4 presents the impacts of PVC through its lifecycle (production, use and disposal loops) and the challenges to replacing it with alternative materials.

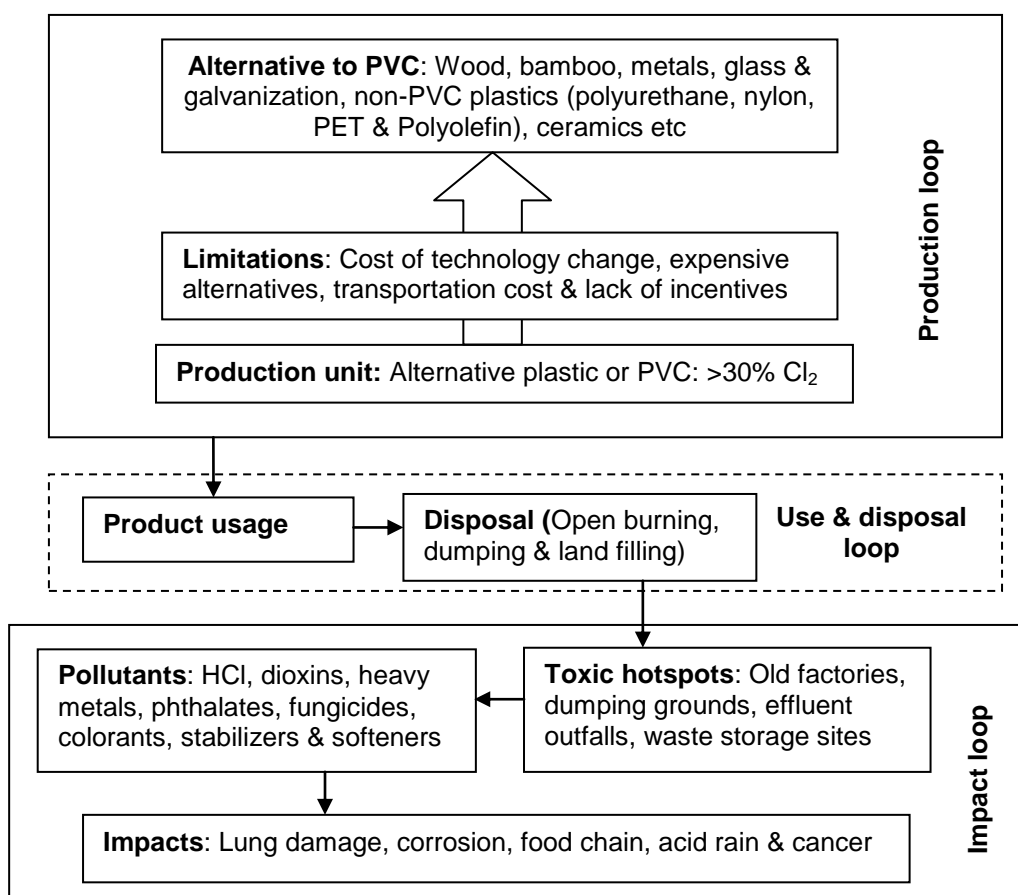


Figure 3.4 Current lifecycle and impacts of PVC

Table 3.1 Main sources and articles to target for PVC recovery

| Main sources                 | Equipment commonly made from PVC  |
|------------------------------|---|
| Medical                      | Colostomy bags, catheters, urine bags, infusion sets, blood bags, gloves, draw sheets & shoe covers   |
| Garden furniture             | Hose pipes, tables & chairs, tarpaulin, padding pools, lawnmower cables, green houses, cold frames & membrane pond liners   |
| Electrical products (≈4%)    | Cable coatings, wheels, stub shafts, office equipment, lamps & electronics  |
| Building construction (≈75%) | Siding in place of timber cladding, insulation, roofing membranes, doors, window & conservatory frames  |
| Furnishing                   | Floor & wall curtains, carpet tiles, & mats, furniture, textiles, imitation & genuine leather, office stationeries (tape, first aid sundries, dish rack, clothes driers, refrigerator shelves & records |
| Children's toys              | Cot mattresses, pens, baby changing mats, nappy covers, bibs, push chair or stroller, tethers, squeeze toys, inflatable toys & dolls  |
| Clothing                     | PVC laminated textiles, shoes, bags & luggage   |
| Packaging                    | Disposable bottles, wrapping, films, trays & jars   |

Identifying major items made from PVC can facilitate sorting leading to effective recovery since its direct use in PG technology is not recommended. Table 3.1 presents the main sources and articles made from PVC to be targeted during plastic waste recovery. Such PVC component could be pre-treated to eliminate HCl before the application in the PG technology.

### 3.4 Options for Combustible Waste Disposal

Table 3.2 Waste plastic collection in Germany 1995

| Fraction  | Quantity (t) | %    | Most appropriate recycling method after sorting  |
|---|--------------|------|--|
| EPS   | 3.500        | 0.6  | Mechanical due to high purity achieved by: (i) using wet techniques involving sink-float and washing which are expensive; (ii) dry technique involving use of air separation with vibrating conveyors, magnetic separators, eddy current separators and sieves |
| Cups  | 10000        | 1.9  |  |
| Bottles   | 53000        | 9.8  |  |
| Films   | 143000       | 26.6 |  |
| Mixed plastics  | 330000       | 61.1 | Chemical or thermal recycling e.g. liquefaction, pyrolysis, gasification and blast furnace   |
| Total   | 540000       | 100  |  |
| <i>Remark: Recycling methods adapted to take-back system of packaging waste</i> |              |      |  |

Source: Adapted from DSD, 1995

Environmental issues are becoming prioritized in most government and community development agendas. This has motivated the search for economically efficient and ecologically effective material and energy recycling technologies (Petts, 2000). Hence, the development and use of strategic technologies driven by recycling credit scheme and the imposition of the landfill tax to preserve landfill void for the future disposal of untreatable residues (Read et al., 1998).

The EC packaging Directives (1994) instituted a take-back system for packaging materials achieving over 80% collection rate in Germany 1995. However, mechanical recycling is hampered by the 61.1% of the mixed plastic rests for which sorting is difficult and expensive favouring thermal recycling (Table 3.2).

### 3.5 Implication of Energy-from-waste on Resource Conservation

According to Nagel (2002) integrated waste management and pollution is identified as fundamental to regional environmental security issues in Africa. Hence, vulgarizing

technologies and know-how to use human waste, garbage and agricultural waste to produce energy reduces dumping while protecting and conserving resources.

### 3.6 Effect of Plastic Component Predominance on Energy Recovery

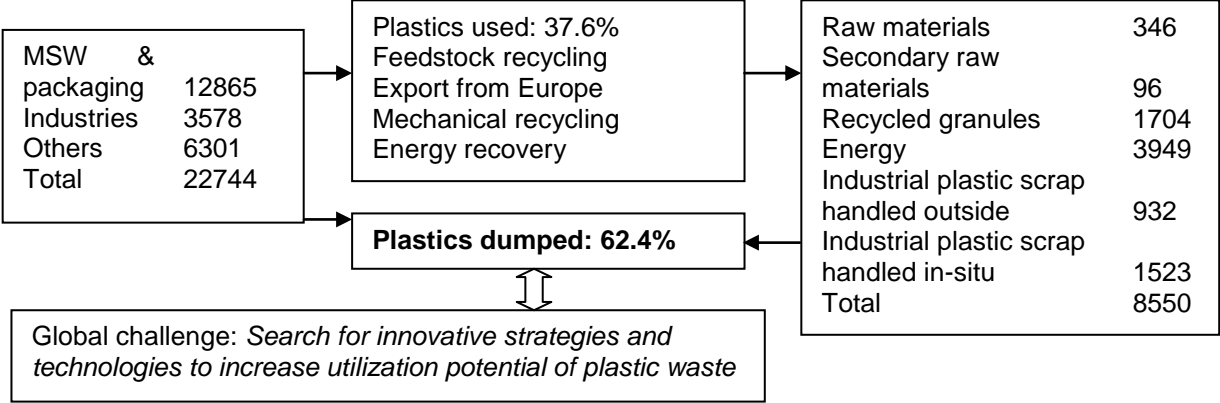


Figure 3.5 Plastic waste utilization potential in Europe in tonnes

Major plastic waste components in MSW in decreasing order of abundance is LDPE>LLDPE>PP>HDPE>EPS>PS>>>PVC & PET. The limited abundance of PVC offers an advantage towards the use of plastics for energy production. Despite the negative environmental challenges resulting from the use of plastics, turning to alternative packaging materials does not offer an economic solution.

Although application of potential results target developing countries where almost 100% of waste plastic at end-of-life is openly burned or dumped, the technology can also be used in developed countries where over 62% of plastic is dumped [data adapted from Hamerton et al. (2003)] (Fig. 3.5). Many studies on pyrolysis of waste plastics (Schlummer et al., 2006; Shoji et al., 2001; Starreveld & Vanierland, 2006; Tachibana & Wakai, 2006; Tsuji et al., 2001; Wu & Williams, 2010; Blazsó, 1997) prove the versatility of the method.

Section one presents a detailed problem analysis, examination of the motivation, justification and objectives for the study while evaluating options for waste, plastic waste and energy production, utilization and management. The next section identifies and describes the integrative methodology applied with justifications for the choices and relevance to achieving the stated research goals.

## Chapter Four

## Description and Justification of the Research Methodology

## 4.0 Rationale for an Integrated Methodology

An integrated methodology that involved the assessment of feedstock characteristics and availability, invention and optimization of the practically usable pyrolysis-gasification technology and evaluation of its social, economic and environmental impacts and application efficiency was adopted. This used international communities with varied socioeconomic, geopolitical and cultural variables as case studies. The methodology was classified into six blocks (I-VI) with the activities carefully chosen to obtain and use relevant primary and secondary data to achieve stated objectives (Fig. 4.1).

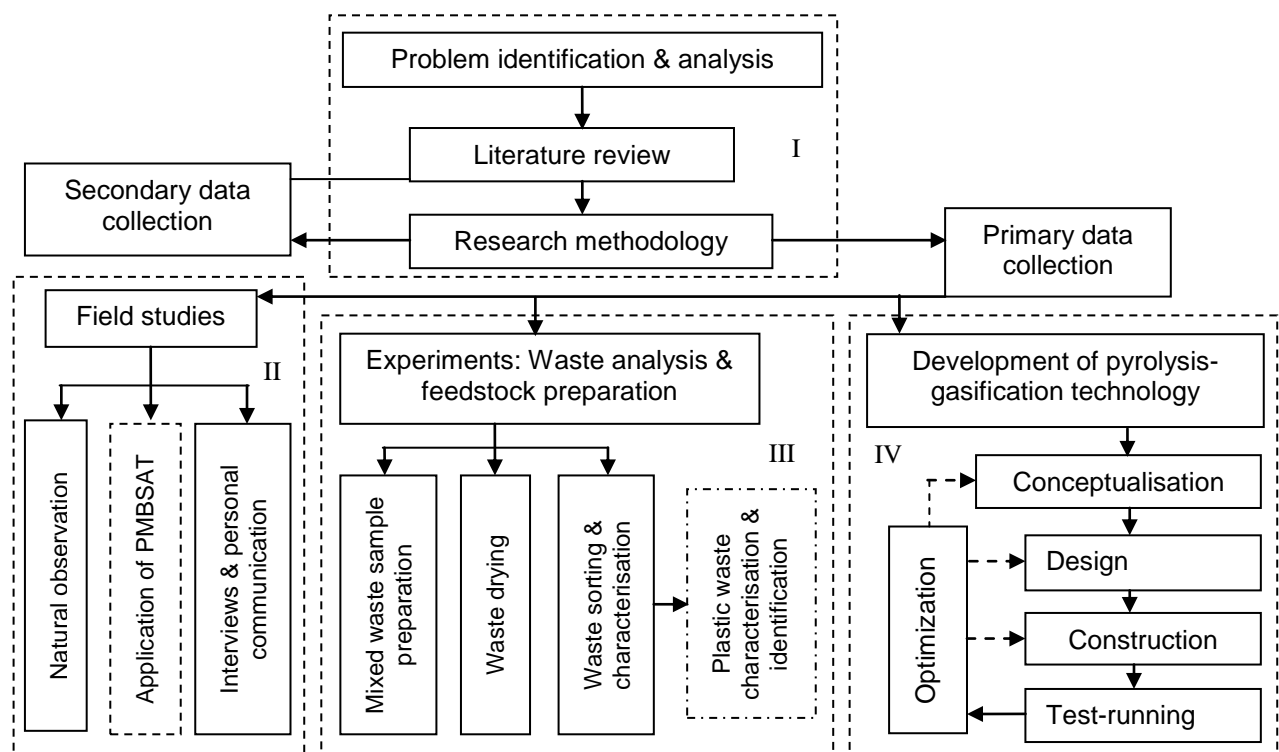


Figure 4.1 Schematic representation of the integrated research methodology

Field, engineering and laboratory studies involving waste and feedstock analysis appropriate to the development and functioning of the PG technology were conducted. This practical problem-solving research used an interdisciplinary application of pure,

applied and social science and engineering skills at various stages. The stages include conceptualization, design, construction, test-running and optimization of a new PG technology that transforms plastic waste to energy. The optimization process involved various construction, laboratory evaluation and statistical analysis (Fig. 4.2).

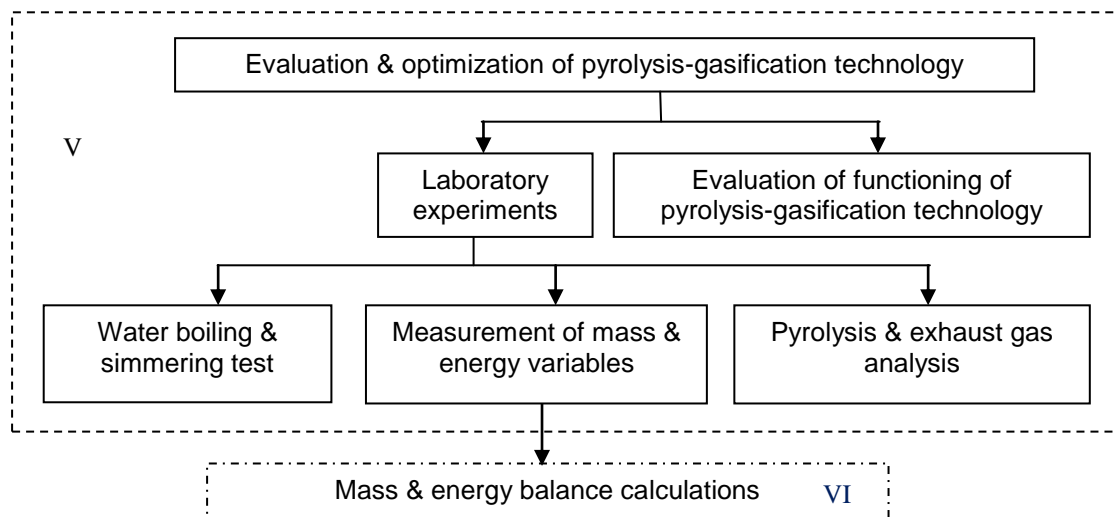


Figure 4.2 Optimisation stages for the PG technology

#### 4.1 Data Collection Sources

Although secondary data sources involving a reviewed peer-reviewed scientific articles and text books due to their authenticity, primary data was prioritise. Emphasis was laid on the acquisition of authentic primary data from field and experimental exercises involving development, evaluation and optimization of the technology.

#### 4.2 Field Studies

Natural observations, interviews and personal communication with experts and stakeholders in waste management operation and services sectors in Cameroon, Nigeria, Benin Republic and Germany were conducted. During the field studies current management practices, waste characteristics and uses of major waste fractions were identified and evaluated. An assessment of plastic feedstock availability, quantity and composition for the application of the PG technology was conducted. Finally, the willingness to accept and pay for the PG technology by potential users was evaluated.

##### 4.2.1 Waste Analysis at BTU Cottbus and STLS Lagos

A waste analysis based on manual sorting under conditions of limited resources and technology was carried out at the BTU Cottbus and Simpson Transfer Loading Station (STLS) Lagos (Fig. 4.3). A sample of mixed waste was collected, weighed and dried

under shade and in open air. This was followed by sorting and weighing of major dry and wet waste fractions with corresponding percentages calculated.



Figure 4.3 Waste pretreatment and sorting for plastic recovery

### 4.3 Sample Characteristics and Representativeness

Waste deposited at the STLS is constantly compacted and movement to the landfill soon after its arrival. Therefore, to get a representative sample of the waste, a mixed sample collected from seven truck loads from varied area and activity zones was collected from an over-the-night disposed consignment. The truck loads were identified to be from market, residential, commercial and general business areas. This sample contain the main components found in the waste disposed at the landfill but for the absence of bulky and special waste components (tires, white waste, metal scrap etc) most of which are recovered by scavengers.

#### 4.3.1 Waste Analysis at STLS: Procedure and Related Observations

The waste sample was taken in four weighed consignments of 42, 46, 40 and 48 kg which sums to 176kg using a 50kg spring balance. The waste was mixed and spread out to dry for 4days under shade from 25<sup>th</sup> to 28<sup>th</sup> May 2010. The waste weighed 150.5kg after drying indicating 25.5kg water lost.

Drying for 8days in open air took place from 29<sup>th</sup> May to 6<sup>th</sup> June, 2010. The regular rainfall for almost all the days for which the waste was constantly covered outdoor made



earlier sorting impossible. Finally, the waste sample was manual sorted on the 6<sup>th</sup> June 2010 despite rain threats by 5 persons. The sorted waste fractions were weighed with weights summed up and subtracted from 150.5kg indicating water lost as 25.8kg.

### 4.3.2 Application of the RESA Approach

Mixed waste was sorted based on potential usage of recovered waste fractions. A resource-recovery scavenging approach (RESA) was developed and used to establish and document the amounts, percentages and types of useful waste fractions in mixed MSW (Appendix V). RESA builds on the sustainability science paradigm of visioning which requires purpose-driven transformation of society at all scales. Such change is guided by the best foresight with insight based on hindsight that science can provide (Kim & Oki, 2011).



Figure 4.4 Composting rich organic waste fraction to bio-fertilizer

This requires the understanding of the nature, cost and principles including a clear vision of waste component end-usage. RESA involves a simulation of mixed waste sorting characterized by:



- Potential uses of the waste fraction within specific communities based on available technology, legislative and prevailing socioeconomic constraints e.g. metals, glass, high calorific value fraction, biodegradable waste and WEEE. Hence, in agric-dependent communities producing 60-90% of biodegradable organic waste, composting to bio-fertilizer offers a cost-effective option (Fig. 4.4).
- Mixed waste sorting to usable fractions is based on basic variables e.g. dominance, size, safety and value
- Material recovery ensures safety of workforce and environment i.e. risky components are recovered first and treated with care.

The RESA involves a purposeful manual waste sorting method highly adapted to developing country situation with limited waste treatment and application technologies. The method takes advantage of the rich putrescible organic content of waste (60-90%) for composting for bio-fertilizers. Applying RESA method at BTU Cottbus, one person sorted 138.3kg of dried heterogeneous commingled waste for 1.5hours (Appendix VI). Sorting duration and labour can be minimized when sorters gain experience or scavengers are employed. RESA is most effective with mixed waste with disproportionately quantities e.g. 60-90% biodegradable organic with limited plastics, paper, metals and glass.



Figure 4.5 Application of RESA in sorting commingled waste



Figure 4.6 Sorting of fine waste fraction

Determination of the weights of the waste fractions was conducted at BTU Cottbus and STLS Lagos following procedure illustrated in figures 4.5, 4.6 and 4.7. Plastic waste fraction in Lagos was made up of 20.1% of total mixed waste and was dominated by PE from light weight packaging materials.

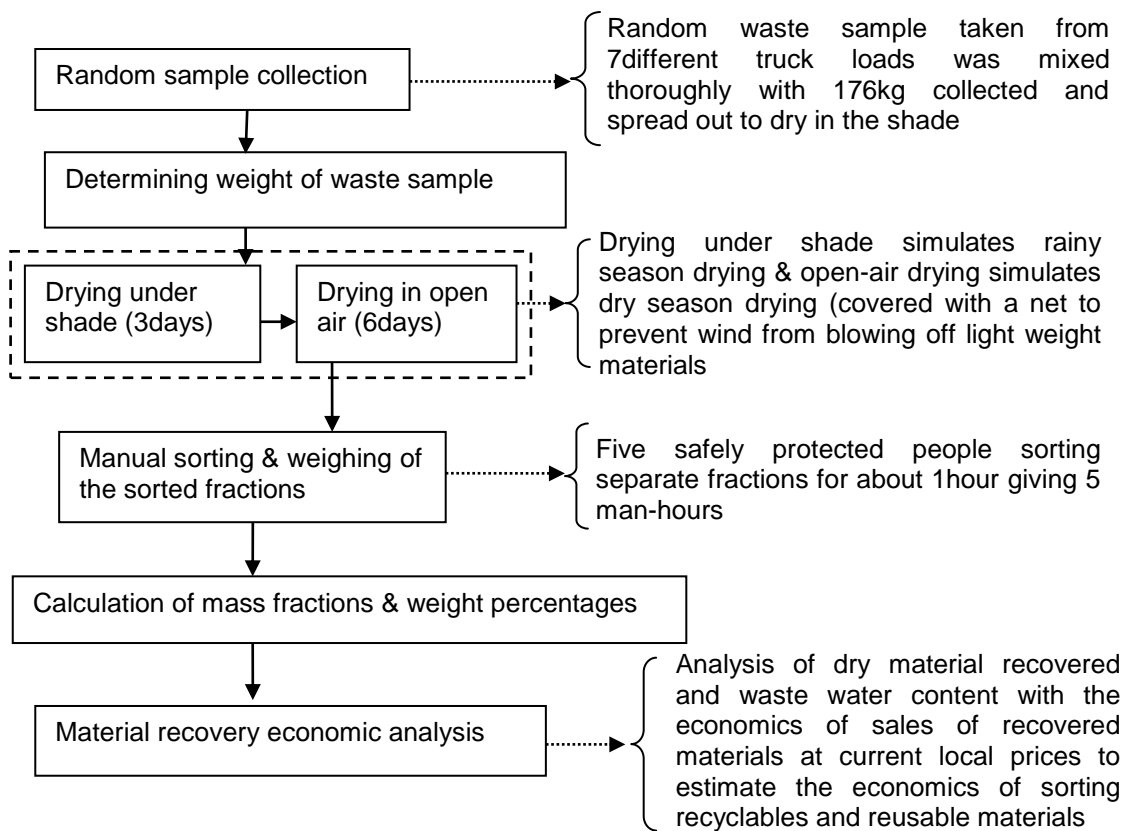


Figure 4.7 Procedure for the waste analysis conducted at STLS Lagos



#### 4.4 Applying RESA in Plastic Waste Fraction Analysis at BTU Cottbus

A plastic waste fraction analysis was not conducted in Lagos since plastic composition was very consistent and dominated by PE of about 95%. This is acceptable for use in the PG technology without any further pre-treatment or sorting. However, after weighing the plastic waste fraction obtained from application of RESA at BTU Cottbus, it was again dried and manually sorted (Fig. 4.8). The unidentifiable components were again weighed and samples collected for further identification.



Figure 4.8 Plastic waste fraction pretreatment and sorting

Samples pieces from the rest of unidentified plastic waste fraction were collected and sorted applying the water sink-float test in order to identify and eliminate PVC. The sink-float test was used as preliminary identification method where components that floated

where discarded and those that sank (sinkers) were collected separately. Again samples from the sinkers were collected for further laboratory identification (Fig. 4.9).

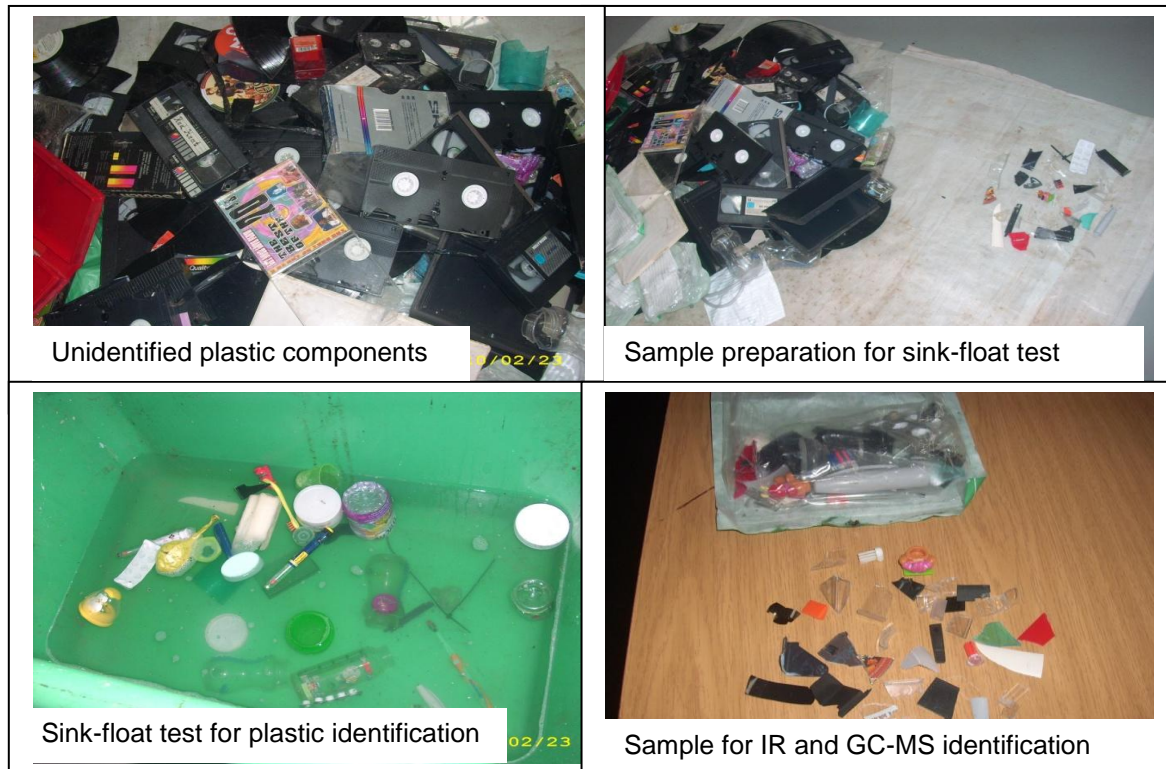


Figure 4.9 Plastic waste identification using sink-float test

Plastics components that floated without air trapping were considered as non-PVC. 36 samples from the plastic components that sank were prepared for further identification using the IR-spectroscopy resulting in 6 PVC, and 30 non-PVC components made up of 12 PS and 18 others single or mixed plastic.

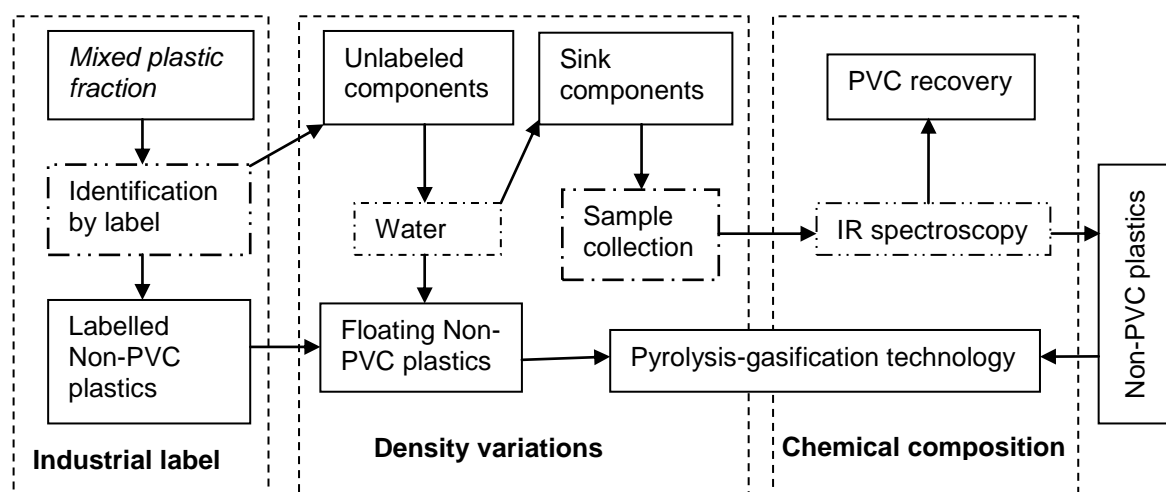


Figure 4.10 Using RESA to separate non-PVC from mixed plastic waste fraction

The fundamental driver to this recovery process is the resource (wealth) value given that scavengers are hardly recyclers themselves. Figure 4.10 shows the procedure for using RESA based on waste plastic properties (industrial label, density variations and chemical composition) to separate non-PVC from mixed plastic waste fraction. While all non-PVC plastic components (free floaters) are acceptable for direct use in the PG technology, PVC needs pre-treatment to eliminate the HCl (Saito & Narita, 2001).

All sample components that sank were recovered and dried followed by preparation of a second set of samples for the infrared (IR) and GC-MS identification. Various plastic identification methods were used to ensure reliable elimination of PVC. However, in most communities where plastic waste composition is relatively consistent, such labour and time intensive exercise may be conducted only once to get baseline data on the waste composition.

#### **4.5 Invention and Optimisation of the PG Technology**

The process involved the conceptualisation, design, construction and test-running with optimisation carried at various stages. At various stages in the invention process of the technology, problems were identified from each experiment and corrected in subsequent experiments within a time dependent and step-wise continuous improvement scheme. Various models of the technology were constructed in Germany while two different models were constructed and tested in Dschang, Cameroon and Lagos, Nigeria.

#### **4.6 Evaluation of the PG Technology**

After the first construction, various experiments were carried out to ascertain the effective functioning of the technology. Major optimization step and processes to minimizing any economic and environmental cost and impacts were conducted. Water boiling and simmering test were carried. Measurement of masses and temperature were determined based on which mass and energy balances were calculated. Pyrolysis and exhaust gas including ash samples were collected and analysed.

#### **4.7 Application of Gas Chromatography-Mass Spectroscopy Technique**

*Gas Chromatography (GC)* involves a mobile phase (inert gas) that carries the sample mixture through a stationary phase into the ionisation chamber. The height of the signal (chromatogram) produced depends on the gas sample concentration while the signal peaks represents the individual compounds in the sample. The time interval from

sample injection (time zero) to elution occurrence is the retention time (RT). This method is useful for evaluating exhaust gas samples to identify any pollutants such as polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs).

*Mass Spectroscopy (MS)* involves electron ionization and mass-charge ratio detection of individual compounds eluted from the GC column. The gas molecules are bombarded with a stream of electrons causing them to break apart into charged ions with a certain mass fragments. These fragments can be large or small pieces of the original molecules depending on the mass-charge ratio (M/Z). Combining GC and MS techniques creates a powerful analytical tool in which samples injected into the instrument are separated into individual components and identified with quantities determined.

All identified VOCs present in the cold pyrolysis gas and condensate, and exhaust gases were extracted in a microfiber with solid phase micro-extraction (SPME). The VOCs were subsequently desorbed from the fibre into a hot injector of a gas chromatograph and analyzed by GC-MS techniques. The GC-MS chromatograms for the pyrolysis gas samples and exhaust gases were compared with the NIST MS spectra database of VOC standard compounds.

## Presentation and Discussion of Results

## Chapter Five

## Municipal Solid Waste Pre-treatment, Analysis and Characterization

## 5.0 Commingled Solid Waste Sample Preparation and Analysis

Water content of MSW determines treatment procedure, impacts and application of various waste fractions. Waste drying reduces moisture and biodegradation processes before manual sorting. Hence, conducting waste drying under shade (simulating in-house drying in rainy season and winter) and outdoor (simulating drying in dry season or summer) gave varied drying rates.

Table 5.1 Mixed MSW sample analysis in Cottbus, Germany

| Mixed Municipal solid waste (MSW) sample analysis in Cottbus, Germany |   |               |   |                        |                         |  |  |       |        |                   |       |  |
|---|---|---------------|---|------------------------|-------------------------|--|--|-------|--------|-------------------|-------|--|
| Items   | MSW sample + bin  | Bin           | MSW sample  | Water lost after 7days | Dried waste after 7days | Remarks: Drying occurred in-doors in winter in heated hall |  |       |        |                   |       |  |
| Quantity/kg   | 224.8   | 62.7          | 162.1   | 23.9 (14.7%)           | 138.3 (85.3)            |  |  |       |        |                   |       |  |
| Waste fraction  | Food waste  | Residue waste | Paper & cardboards  | wood                   | Textiles & Napkins      | Mixed plastics   | WEEE   | Glass | Metals | Others            | water | High waste /water content requiring drying |
| Mass/kg   | 13.90   | 32.00         | 27.30   | 0.28                   | 20.22                   | 24.60  | 2.10   | 13.20 | 4.60   | 0.07              | 23.80 |  |
| Mass /%   | 8.57  | 19.74         | 16.84   | 0.17                   | 12.48                   | 15.18  | 1.30   | 8.14  | 2.84   | 0.04              | 14.70 |  |
| Usable fraction/%   | 10.06   | 23.15         | 19.75   | 0.02                   | 14.63                   | 17.80  | 1.52   | 9.55  | 3.33   | Eliminated        |       |  |
| Material & energy recovery potential (wt %)                           | Biogas or/and composting: 33.21%  |               | 52.2% of usable waste fraction is applicable as feedstock in PG technology or control incineration with energy recovery |                        |                         |  | Reusable or recyclable to secondary raw materials: 14.40 |       |        | Land filled: 0.19 |       |  |
| <b>Remarks</b>  | <ul style="list-style-type: none"> <li>● 99.81% of waste has energy &amp; secondary material recovery potential</li> <li>● An almost zero waste scenario with only 0.19% to land field is achievable</li> </ul> |               |   |                        |                         |  |  |       |        |                   |       |  |

The consequent waste analysis based potential uses of various waste fractions is shown in table 5.1. Environmental conditions (temperature, windy condition and waste exposure surface area) and moisture content of the waste influence drying rate (Fig.

5.1). Drying in winter occurred at normal room temperature. The waste was collected in protected bins reduces moisture content, labour and time spent in drying.

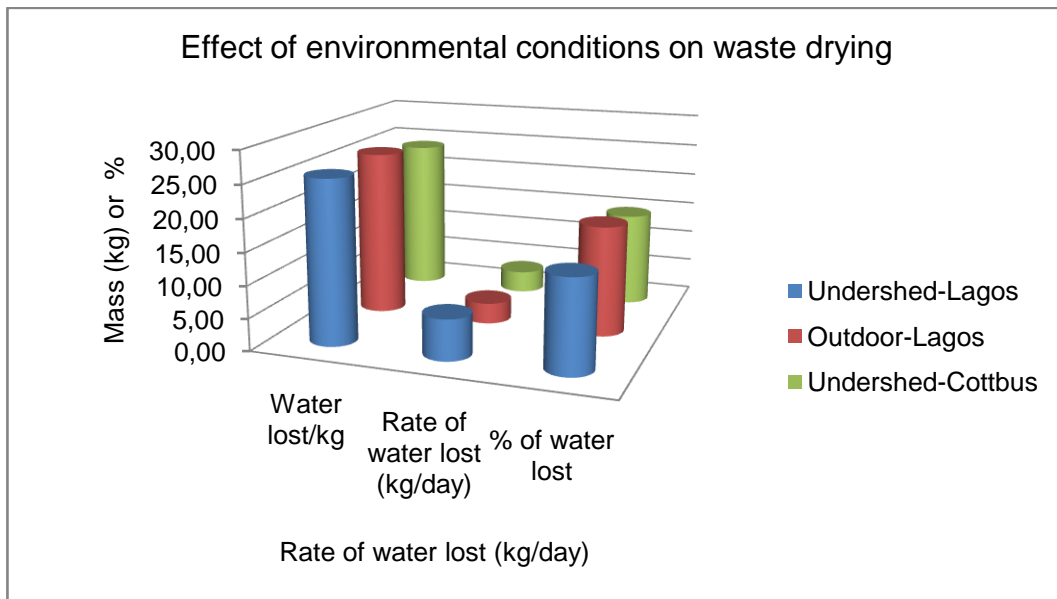


Figure 5.1 Effect of environmental conditions on rate of waste drying

### 5.1 Moisture Minimization and Impacts on Waste Management Services

Minimizing waste moisture content is fundamental to effective waste management. The polluting impacts of waste on humans and environment are influenced by weather condition such as in dry and rainy seasons in tropical countries. Observations and conclusions drawn with respect to the drying processes include:

#### *Under-the-shade drying*

- Significant drying occurred with a loss of 25.5kg of water to drying in the shade giving a dry rate of 6.38kg (6.38litres) per day
- Although drying in the shade was with daily mixing, there was some slight fermentation as perceive from the smell of the waste
- Fermentation produces heat enhancing the drying process

#### *Outdoor drying*

- Drying outdoor in open air led to 25.8kg of water lost in 8days at the rate of 3.23kg (3.23litres) per day
- The drying rate certainly will be higher if there was constant sun shine and waste was exposed to the sun continuously. However, caution is required because covering could lead to heat conservation accelerating drying even at night.



- Outdoor drying did not indicate significant smell production indicating absence or minimal fermentation
- A net was used to prevent the wind from blowing away light particles during outdoor drying

## 5.2 Implication of Moisture on Waste Handling

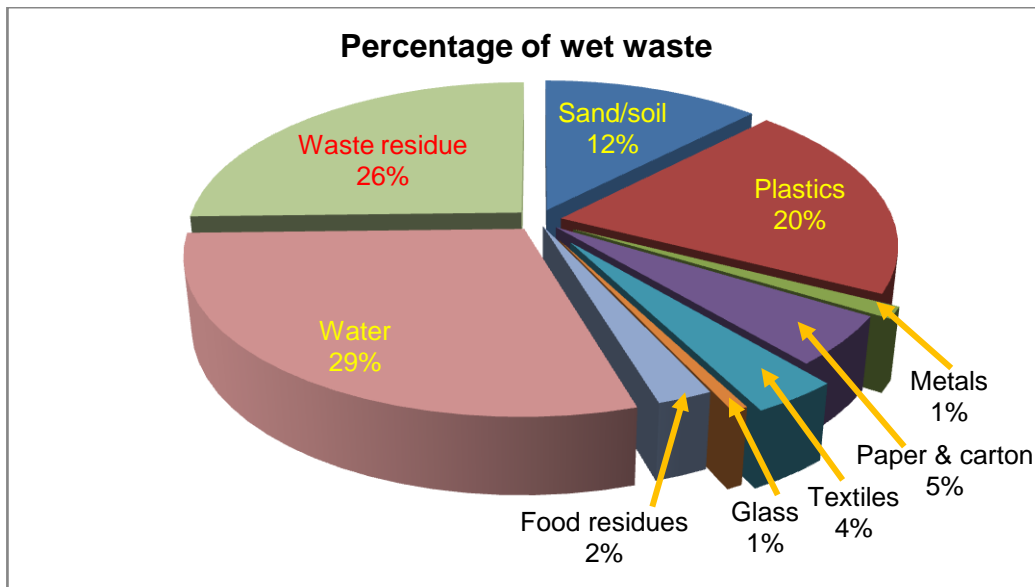


Figure 5.2 Percentage of wet waste components

Although the percentage abundance of dried waste is similar to that of wet waste (Fig. 5.2), the higher percentage values are due to moisture content. Moisture increase potential handling, transportation and sorting costs. This implies that, waste collected using protected bins will require less drying and will have reduced weight percentages (Fig. 5.3). Composting the waste before sorting may require no drying. However, the presence of hazardous impurities can affect bio-fertilizer quality which should be carefully evaluated.

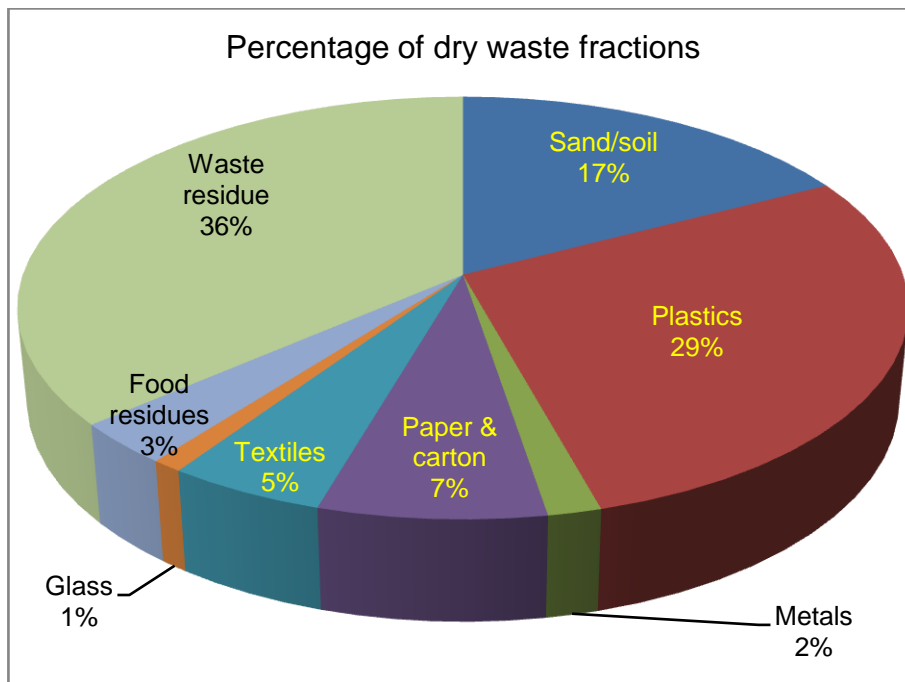


Figure 5.3 Weight percentages of dry waste components

### 5.3 Implications of the Waste Analysis on Waste Management Practice



Figure 5.4 Protection of waste from rain and wind during drying

- Drying took about 13 days in Lagos due to interruptions or threats from rain indicating that successful waste sorting must be done under shelter (Fig. 5.4).
- Presence of medical waste components (drip set, blood bags and injection needles) in the municipal waste sample (in Lagos) proved that strict preventive health, safety and risk management strategies during sorting are required.

A critical evaluation of the context-adapted waste analysis exercise identifies activities and motivations for actions including advantages and limitations. A waste analysis

exercise vis-à-vis its application in a cost-effective waste-to-resource management approach is offered. Wealth value of waste increases when collection, transportation and disposal costs are reduced by minimizing moisture using protected bins (Fig. 5.5).



Figure 5.5 Sample protected bins to minimize waste moisture

**5.3.1 A Waste-to-Wealth Analysis Approach**

Effective waste management in consumer economies of developing countries should consider incentives for public participation. Such incentives should target economic, social, cultural and environmental variables depending on waste characteristic, quantities and potential application. Table 5.2 examines a resource valuation model driven by bottom-up value addition through sorting and utilization of various waste fractions. Since biodegradable market waste in Lagos is collected and transferred directly to composting site, quantity of bio-waste in the sample above should be considered with caution. Any waste component which can be sold or exported in exchange for money is said to have wealth value. Since waste is generally free, its wealth value is equal to the labor used for sorting and handling.

Table 5.2 Waste-to-wealth analysis approach

| Waste fraction   | Weight (kg) | Weight % | Local prices /kg           | Main components   | Remarks, value adding & utilization potential of sorted waste fraction                                    |
|------------------|-------------|----------|----------------------------|---|---|
| Residue          | 45.30       | 25.74    | Non                        | Organic biodegradable fine particles too small to sort                | Can be composted for manure or combusted to energy  |
| Sand & dust      | 21.60       | 12.27    | Only sand has market value | Sand, soil & dust particles mixture                                   | Sand resulting from street sweeping can be cleaned by winnowing and sieving for use in construction works |
| Plastics         | 35.40       | 20.11    | Depends on type            | Light weight packaging materials, bottles, drip set & pure water bags | Very high fraction which can be pelletized, recycled or pyrolysed for chemical & energy production        |
| Metals           | 2.10        | 1.19     | Depends on type            | Cans, tins and cables   | Readily recyclable even locally and has ready market  |
| Paper & cartoon  | 8.90        | 5.06     | Varies                     | Newspapers, cartoons & papers   | Recyclable to toilet paper or pelletized or incinerated for energy production                             |
| Textile material | 6.20        | 3.52     | Depends on state           | Tailoring shop waste, clothes, leather & shoes                        | Combustible for energy production   |
| Glass            | 1.20        | 0.68     | Depends on bottle          | Bottles and broken glass pieces                                       | Recyclable locally but bottles are marketed for reuse   |
| Food remains     | 4.00        | 2.27     | High compost value         | Food stuffs and kitchen refuse  | Digested for biogas production or composted to manure without biogas collection                           |
| Water            | 51.30       | 29.15    | Non                        | Water evaporated  | Evaporates on drying  |

### 5.3.3 Strategies for Waste Reduction

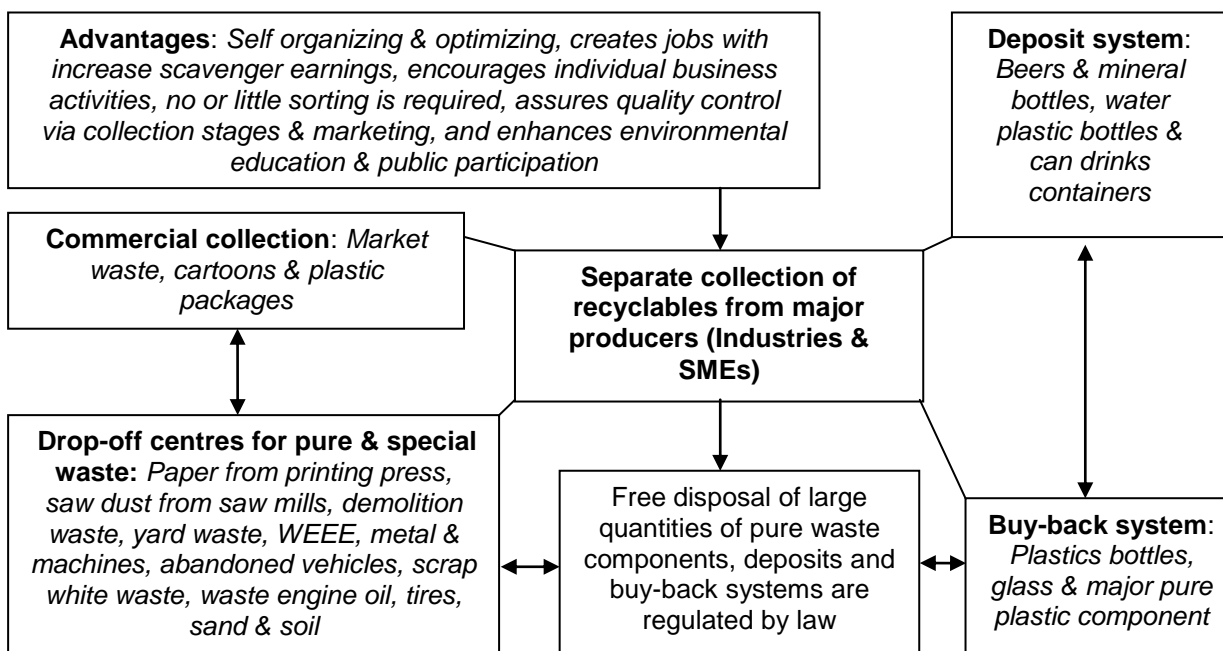


Figure 5.6 Modelling an appropriate community waste reduction system

Waste reduction minimizes landfill space consumption including collection, processing and transport costs (Leskens et al., 2005). Figure 5.6 presents a waste reduction

strategy that focuses on the separate collection of pure waste from industries. A deposit system for predominant waste fraction (plastics, wood and food waste, glass and bottles) and buy-back schemes that provides incentives for scavenging and public participation are emphasized. This requires waste characterisation with identification of sources relevant to designing and implementing a take-back system.

## Chapter Six

### Characterisation of Plastic Waste Fraction and Feedstock Preparation

#### 6.0 Plastic Waste Recovery and Analysis

The value a waste fraction depends on the composition and purity. In order to convert plastic waste into energy with minimum environmental pollution, diverse inventions and pyrolysis technologies for producing liquid fuels have been developed. These fuels are then burned to produce energy. The energy potential of any fuel depends on breaking of C-C and C-H bonds liberating heat at high temperature. Table 6.1 indicates the composition, quantities, percentages and characteristics of plastic waste recovered from a sample of mixed MSW in Cottbus, Germany.

Table 6.1 Mixed plastic waste fraction analysis at BTU Cottbus

| Mixed plastic waste fraction analysis  |   |                                  |                        |                                |                   |   |       |           |       |      |   |
|--|---|----------------------------------|------------------------|--------------------------------|-------------------|---|-------|-----------|-------|------|---|
| Items  | Mass of plastic waste /kg   | Mass lost after 1 week drying/kg | Weight % loss of water | Mass of dried plastic waste/kg | Waste to landfill | Final weight of plastic waste characterized |       |           |       |      |   |
| Quantity/kg  | 24.6  | 2.00                             | 8.13                   | 22.6                           | 0.20              | 22.40                                       |       |           |       |      |   |
| Plastic type /code   |   | PE1: 1                           | HDPE : 2               | PVC:                           | LDPE: 4           | PP: 5                                       | PS: 6 | Others: 7 | Total | Lost |   |
| Mass of identifiable plastic types/kg  | 0.26  | 1.09                             | 0                      | 0.30                           | 3.50              | 0.35  | 16.90 | 22.40     | ---   |      | <ul style="list-style-type: none"> <li>• Identifying plastic components needs integration of various methods</li> <li>• PVC is not common in plastic packaging but about 1-2% by weight was found in the unlabelled fraction</li> </ul> |
| Percentage of identifiable plastic /%  | 1.16  | 4.80                             | 0                      | 1.31                           | 15.49             | 1.57  | 74.78 | 99.11     | 0.89  |      |   |
| Percentage of usable identified plastics /%  | 1.17  | 4.84                             | 0                      | 1.32                           | 15.63             | 1.58  | 75.46 | 100.00    | ---   |      |   |
| Identification of unlabelled plastics  | IR-spectroscopy identification leads to 6 components made from PVC (Tablet package, video cassettes, baby feeding bottles & drip set pipe). |                                  |                        |                                |                   |   |       |           |       |      |   |
| <i>Others: PC, PBT, PU, polyester, poly vinyl acetate, alkyl resins, polyamide, ABS, acryl nitrile (AS), silicone)</i> |   |                                  |                        |                                |                   |   |       |           |       |      |   |

#### 6.1 Utility-objective-oriented Sorting

Figure 6.1 presents the results of the utility-objective-oriented sorting of commingled waste and mixed plastic waste analysis. The mixed plastic formed 17.8% of total waste made up of identifiable (25.22%) mainly of LDPE and HDPE, and unidentifiable (74.78%) plastic components (Fig. 6.1).

Most of the unidentified plastics resulted from old plastic equipments which are currently being faced out e.g. record plates, VHS video cassettes etc. Plastic identification in

Cottbus complicate by the high variety compared to Lagos where 20.11% of the mixed waste was mainly light weight packaging plastics, water bottles and 'pure water' sachets made from PE, PP and PET.

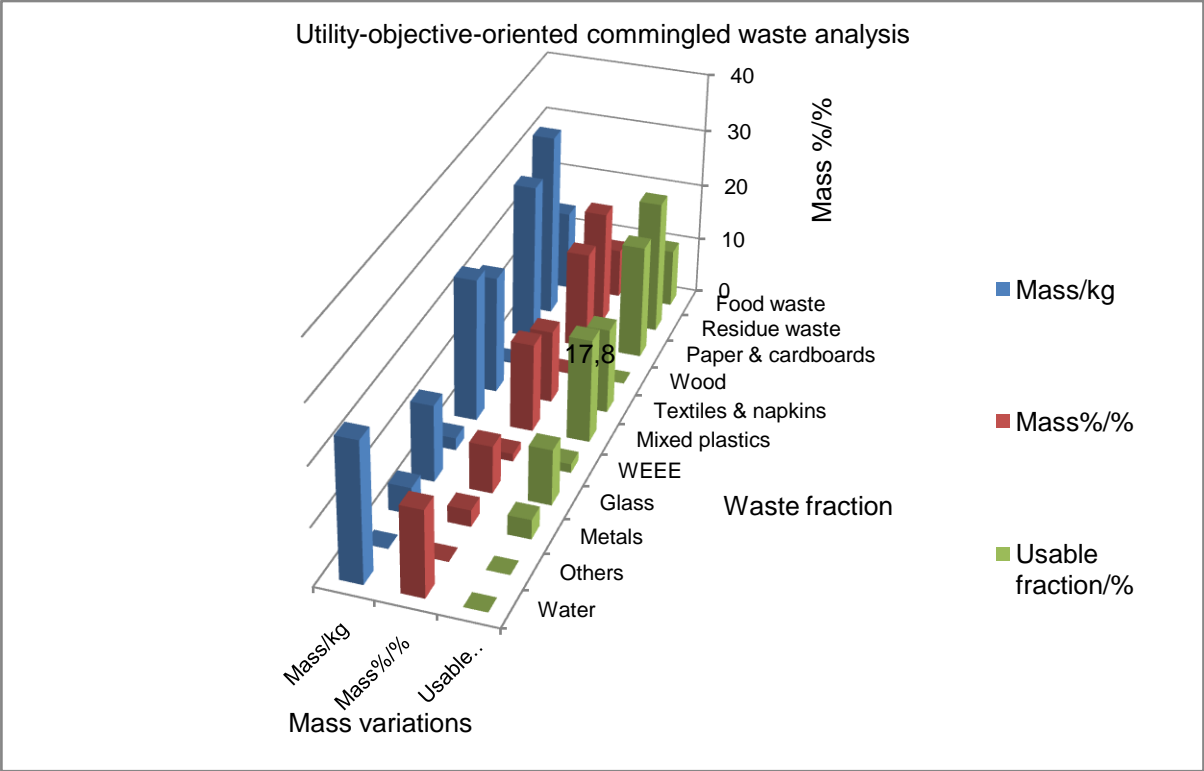


Figure 6.1 Application of RESA in commingled waste characterisation

**6.2 Application of RESA**

RESA was applied at BTU Cottbus to obtain usable fractions from dried waste. Recyclable materials composed of metals and glass formed about 12.88%. The rest of 87.12% is made up of materials that can be converted to energy (Fig. 6.2). On the other hand, in Lagos 3% is made up of metals and glass while 97% is composed of material that can be converted to energy and/or composted to manure (Fig. 5.3). However, the result in Lagos should be taken with caution since informal sector scavenging targets recyclables. In Cottbus, mainly plastic and glass bottles with deposit are recovered by the informal scavenging in a society where separate waste collection is so advanced and widely practiced.

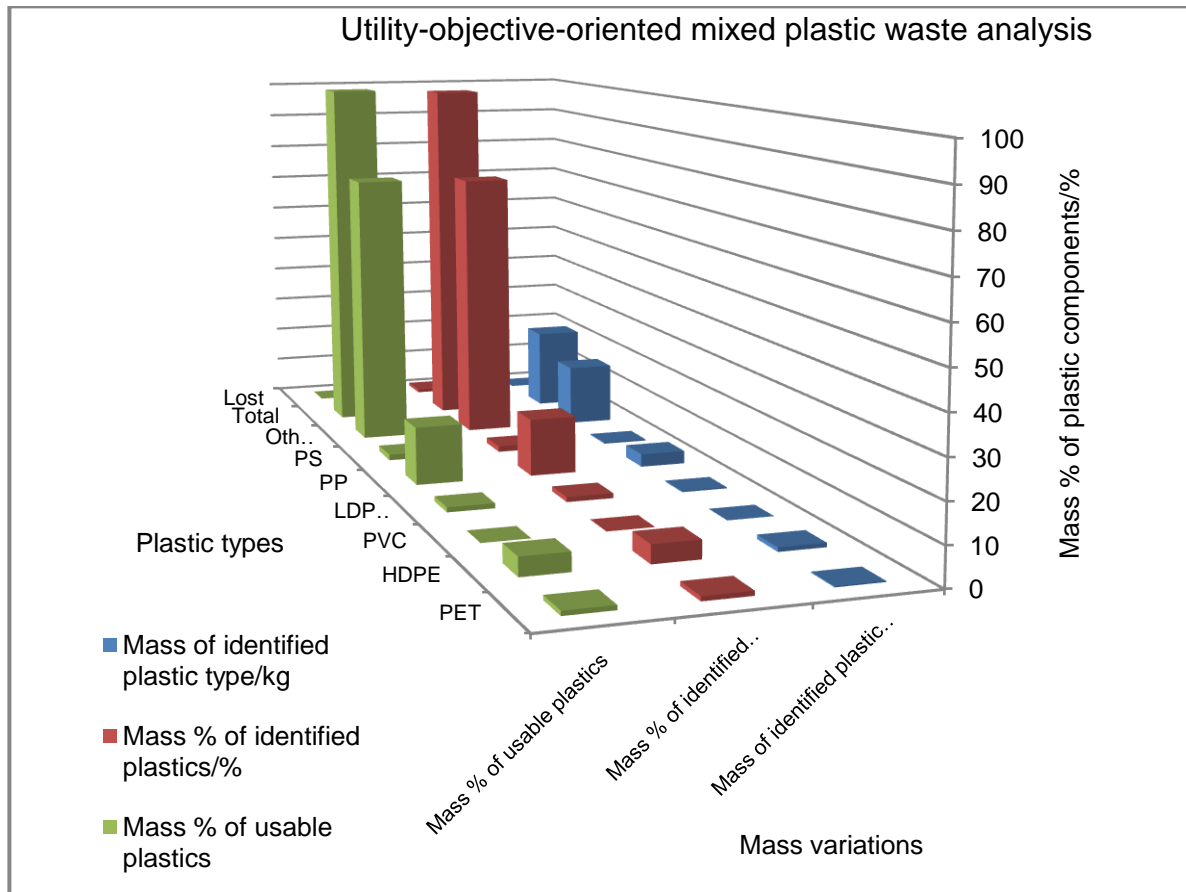


Figure 6.2 Composition of mixed plastic waste at Cottbus

### 6.3 Plastic Waste Identification Using the IR-Spectroscopy

IR-spectroscopy was used to identify unlabelled plastic components from mixed waste. The spectra obtained from each plastic sample were compared with a standard database for polymers as illustrated in appendices I and II (Fig. 6.3). Most of the plastics were classified as:

- Pure hydrocarbons (HDPE, LDPE and PP) with almost 100wt% of volatile matter (C, H) with average calorific value of 46.5MJ/kg) and PS with 99.8wt% of volatile matter (C, H) with calorific value of 42.1); and
- Halogenated polymers such as PVC (with 94.8wt% of volatile carbon and fixed carbon of 4.8wt%) (Sorum et al., 2000) and nitrogen containing polymers and silicone



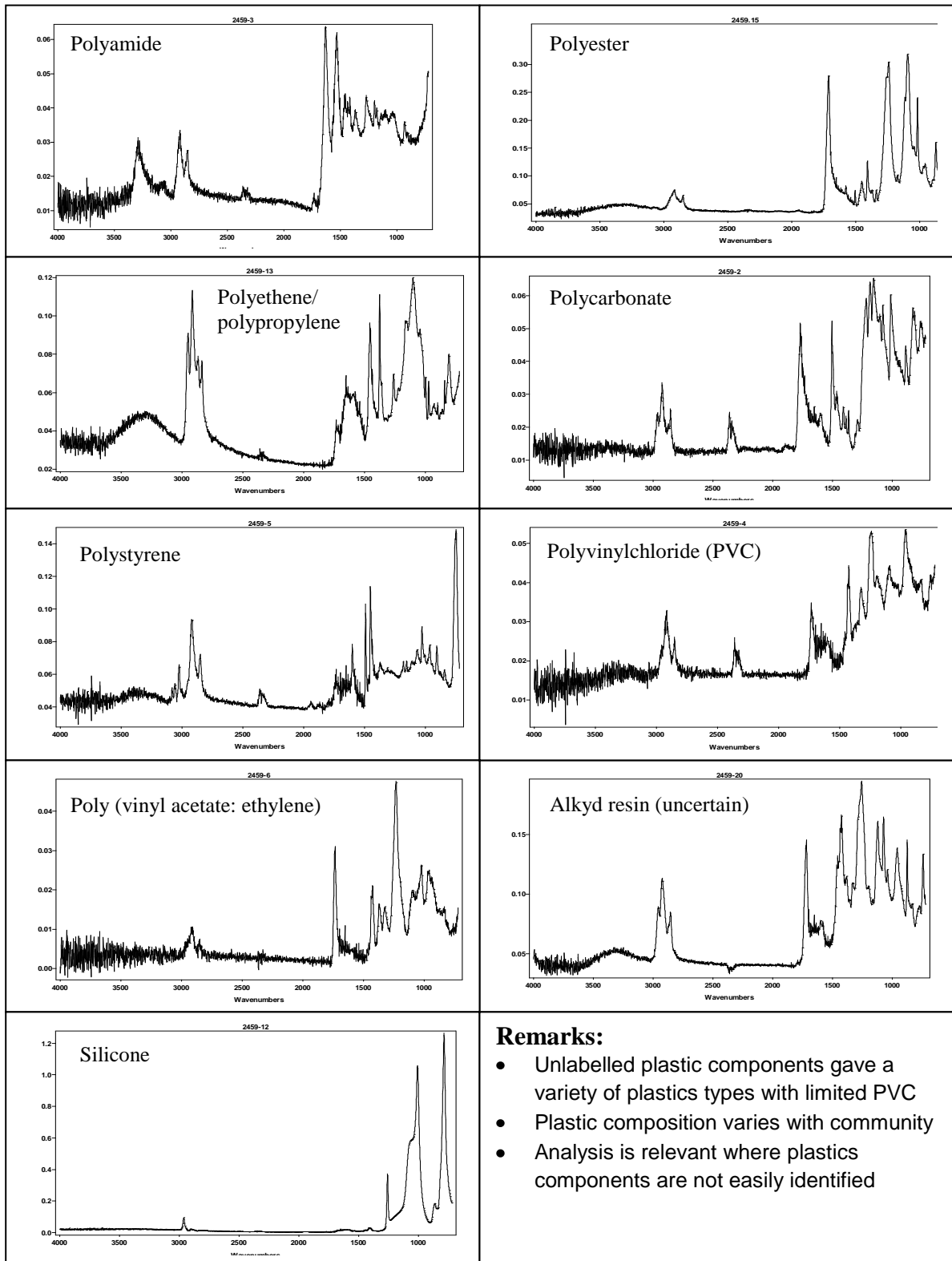


Figure 6.3 Spectra of unidentified waste plastic components

Table 6.2 Modern waste plastic recycling plants costs estimates

| Technology           | Plant capacity (tone/day)   | Capital cost (MUS\$) | O&M Cost (MUS\$) | Planning to commissioning (months) |
|----------------------|---|----------------------|------------------|------------------------------------|
| Pyrolysis            | 70-270  | 16-90                | 80-150           | 12-30                              |
| Gasification         | 900   | 15-170               | 80-150           | 12-30                              |
| Incineration         | 1300  | 30-180               | 80-120           | 54-96                              |
| Plasma gasification  | 900   | 50-80                | 80-150           | 12-30                              |
| Anaerobic digestion  | 300   | 20-80                | 60-100           | 12-24                              |
| In vessel composting | 500   | 50-80                | 30-60            | 9-15                               |
| Sanitary landfill    | 500   | 5-10                 | 10-20            | 9-15                               |
| Bioreactor landfill  | 500   | 10-15                | 15-30            | 12-18                              |
| <b>PG Technology</b> | <b>500</b>  | <b>0.5-1</b>         | <b>0.25-0.5</b>  | <b>3-4</b>                         |
| PG Technology        | Comparative cost estimate based on tonnage would be 10-20% of above mentioned amounts for equivalent large scale application while small scale application will need a few tens of thousand dollars and household usage will need 50-150 dollars depending on the plant size. |                      |                  |                                    |

(Source: Adapted from World Bank-Carbon Finance Unit, 2008, except data on PGT)

#### 6.4 PG Technology Milestones Achievements

The cost-effectiveness and affordability of current plastic waste technologies is influenced by design, construction, installations, energy and running cost (Table 6.2).

Hence, simplifying the process to minimize investment costs makes the energy recovery technology affordable for low income communities. Plastic waste fraction from MSW contains 95-99% of LDPE, HDPE, PP and PS with average calorific value of 45.4MJ/kg. Table 6.3 presents an estimate of energy lost by land filling plastics in some cities. Employing the PG technology efficiently balances the economic, environmental and social pressures of sustainable energy and waste management demands by:

1. Meeting national and international communities' renewable energy targets
2. Fulfilling increasingly stringent corporate social responsibility targets and obligations
3. Supplementing and substituting for traditional fuel sources which are becoming more expensive with rising energy demand and price
4. Maximizing energy production from renewable fuel sources and waste
5. Building affordable, adaptable and scalable 'energy from waste' clean and controllable technological solutions

Table 6.3 Annual plastic waste generation rates with energy lost in some cities

| City /countries                | Population /M | Population density/km | Average Temp/°C | Rainfall /mm | Waste GR kg/person/day | % Plastic | Annual plastic waste /tonnes | Annual energy lost /MMJ |
|--------------------------------|---------------|-----------------------|-----------------|--------------|------------------------|-----------|------------------------------|-------------------------|
| Amman /Jordan                  | 2.13          | 3089                  | 26              | 230          | 1.02                   | 16        | 126582                       | 5.7                     |
| Buenos Aires/ Argentina        | 2.78 (2001)   | 13676                 | 17              | 1200         | 0.98                   | 14        | 138875                       | 6.3                     |
| Conakry /Guinea                | 2.00          | 4444                  | 27              | 4293         | 0.40                   | 5         | 14600                        | 0.6                     |
| Kathmandu /Nepal               | 1.10          | 1895                  | 13              | 2000         | 0.40                   | 8         | 12836.32                     | 0.6                     |
| Lahore /Pakistan               | 8.00          | 4515                  | 20              | 500          | 0.65                   | 9         | 1708200                      | 77.6                    |
| Sarajevo Bosnia & Herzegovinia | 0.41          | 334                   | 17              | 1200         | 1.20                   | 13        | 23345.4                      | 1.1                     |
| Shanghai /China                | 17.80         | 2808                  | 15              | 1400         | 0.96                   | 19        | 1185052.8                    | 53.8                    |
| Kawasaki /Japan                | 1.33          | 9215                  | 17              | 1932         | 1.01                   | 14        | 68487.8                      | 3.1                     |
| Atlanta, Georgia, USA,         | 0.44          | 1289                  | 16              | 1270         | 1.72                   | 19        | 52722.64                     | 2.4                     |
| Lagos /Nigeria; 2011)          | 17.55 (2006)  | 4193                  | 27              | 1507         | 0.50                   | 15        | 480486                       | 2.1                     |
| Cottbus /Germany               | 0.10          | 623                   | 9               | 547          | 1.15                   | 9         | 3863.32                      | 0.2                     |

In order to achieve this goal based on knowledge of the plastic feedstock availability, composition and quality, various energy-based options for sustainable plastic waste management were evaluated. Drawing on the strength and trying to mitigate identified weaknesses of current state-of-the-art technologies, a self-sustaining PG technology was conceived, designed, tested and optimised.

## Chapter Seven

### Energy-based Options for Sustainable Plastic Waste Management

#### 7.0 Conversion of Plastic Waste into Energy

The ability of plastics to crack at high temperature (300-600°C) releasing various combustible hot gases offers multiple energy production opportunities. Although the gases are generally cooled to obtain liquids which are then fractionally distilled to produce fuels, they could be burned in-situ.

#### 7.1 Mass and Energy Conversions within the PG Process

Although various plastics have different activation energies, they typically decompose on thermal cracking yielding a light gaseous fraction. The light fraction composed mainly of alkanes, alkenes, hydrogen, carbon monoxide, carbon dioxide and other high-boiling-point hydrocarbon products increase with rise in temperature. Figure 7.1 illustrates the flow of materials (hard arrows) and energy (dotted arrows) during cracking of plastics in the presence of water (steam) to the light fraction which is burned in-situ in a self-sustained system.

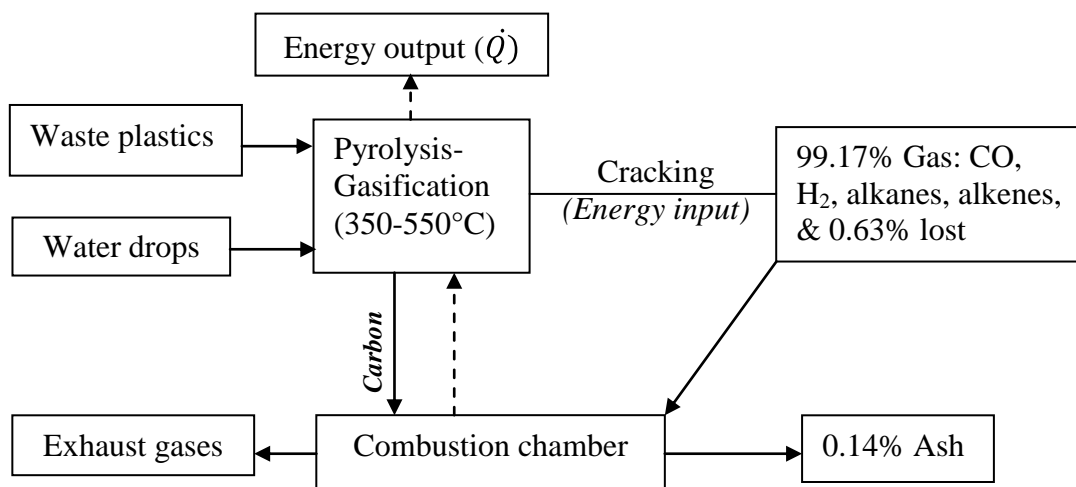


Figure 7.1 Mass and energy conversion within the plastic PG process

#### 7.2 Mass Changes during Thermal Cracking of Major Polyolefin

Catalyst and thermal cracking conversions yield 7.8% and 0.14% of coke respectively. Use of catalyst leads to low conversion rate and higher waste for the landfill. Considering the extra cost of both catalyst and chamber installations as well as treatment due to poisoning, thermal cracking is preferred. Hence, the PG process uses thermal cracking preferably since product selectivity is immaterial and catalyst cost can

be avoided. Table 7.1 gives all possible product yields from the pyrolysis of various non-halogenated plastics.

Table 7.1 Comparison of products of the thermal and catalytic cracking of polyolefin

|                    |                               |  |  |              |                            |        |         |
|--------------------|-------------------------------|--|--|--------------|----------------------------|--------|---------|
| Thermal cracking   | Property                      | HDPE   | LDPE   | LP           | PP                         | PS     | Average |
|                    | Liquid yield (%)              | 91.30  | 91.71  | 93.80        | 91.05                      | 99.02  | 93.38   |
|                    | State of liquid               | Milk white   | Milk white   | Milk white   | Yellow                     | Rufous |         |
|                    | Product at normal temperature | Wax  | Wax  | Wax          | Solid & liquid mixture     | Liquid |         |
|                    | Gas yield (wt %)              | 7.61   | 7.42   | 5.60         | 7.60                       | -      | 7.06    |
|                    | Coke yield (%)                | 0.14   | 0.15   | 0.14         | 0.14                       | 0.15   | 0.14    |
|                    | Total yield (%)               | 99.05  | 99.28  | 99.54        | 98.79                      | 99.17  | 99.17   |
| Lost (%)           | 0.95                          | 0.72   | 0.46   | 0.21         | 0.83                       | 0.63   |         |
| Catalytic cracking | Liquid yield (%)              | 76.81  | 77.40  | 85.20        | 87.20                      | 86.20  | 82.57   |
|                    | State of liquid               | Solid +  | Solid +  | Light yellow | Light yellow               | Rufous |         |
|                    | Product at normal temperature | Liquid mixture   | Liquid mixture   | Liquid       | Liquid                     | Liquid |         |
|                    | Gas yield (wt %)              | 14.08  | 14.08  | 8.15         | 9.34                       | 0.34   | 9.20    |
|                    | Coke yield (%)                | 8.04   | 8.04   | 6.52         | 3.35                       | 13.02  | 7.80    |
|                    | Total yield (%)               | 99.79  | 99.79  | 99.87        | 99.89                      | 99.56  | 99.78   |
|                    | Lost (%)                      | 0.21   | 0.21   | 0.13         | 0.11                       | 0.44   | 0.22    |
| Other properties   | Temperature range (°C)        | 400-450  | 420  |              | 450-640                    |        | 400-640 |
|                    | Conversion rate (%)           | 95% oil products   |  |              | 50-80% in catalyst & water |        |         |
|                    | Characteristic products       | Oil: C <sub>10</sub> -C <sub>30</sub> (94.5%); Gas: H <sub>2</sub> , C <sub>1</sub> -C <sub>5</sub> (5.5%) | Olefins (65%); Terminal olefin (35%); Non terminal olefin (5%) |              | Qualified gasoline for use |        |         |

Source: Adapted from Kaminsky et al., 2006

Although the PG technology does not lead to liquid (condensed gaseous molecules) and gas collection, it is assumed that total yields of 99.78% (compared to 99.17%) represents the gases produced which can be burned in-situ (Fig. 7.2). Burning the hot gases eliminates any phase changes and major impacts of burning fuels.

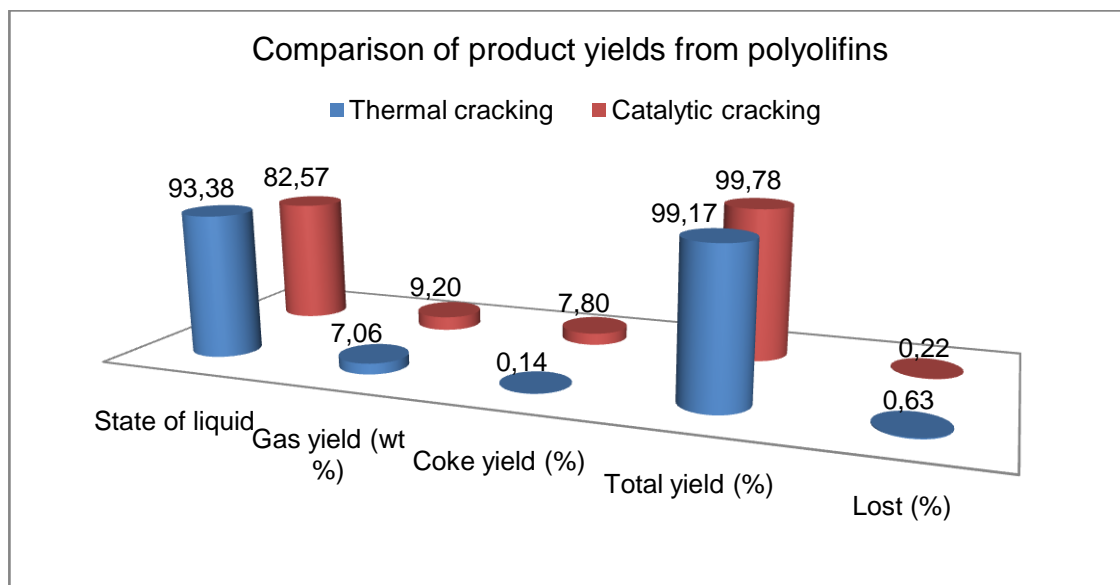


Figure 7.2 Comparison of product yields from thermal and catalytic cracking

### 7.3 Impacts of Catalyst Application

Despite the limitation to yields, the use of catalyst increases the rate of the chemical conversion reaction while:

- Lowering activation energy of the reaction (cracking)
- Reducing the process energy consumption
- Increasing the treatment efficiency
- Improving product selectivity and product quality

However, in the PG technology catalyst application is optional.

### 7.4 Main Types and Characteristics of Waste Plastics Pyrolysis Processes

Thermal cracking is cheap with simple operation but has high energy consumption and low conversion rate. It yields of straight chain products with poor selectivity and quality. Such hydrocarbons have low oil product yields with gasoline containing large amounts of olefins with low RON value, high freezing point and low cetane value. In contrast, using catalyst and cracking-catalytic reforming lowers the activation energy and improves treatment efficiency, product quality and selectivity.

Table 7.2 shows a comparative assessment of state-of-the-art industrial processes using pyrolysis to convert plastic waste to fuels and chemical feedstock. These technologies are expensive with limited large industrial and commercial applications.

Table 7.2 Comparison of typical pyrolysis process of waste plastics

| Developer  | Scale      | Feedstock                          | Reactor                    | Temp. (°C)                  | Catalyst                                  | Main products  | Product yield (%)   |
|--|------------|------------------------------------|----------------------------|-----------------------------|---|--|---------------------|
| United Carbon Company                            | 35-70kg/d  | PE, PP, PS, PVC, PA, PET,          | Extruder                   | 420-600                     |   | wax  |                     |
| Japanese Carbon Company                          |            | PE, PP, PS                         | Extruder                   | 500-600                     |   | Monomers   |                     |
| Fuji Recycle Company                             | 5000t/a    | PE, PP, PS (industrial waste)      | Melting furnace            | 390                         | ZSM-5                                     | Gasoline, kerosene, diesel oil   | 80-90               |
| Fuji Recycle Company                             | 4000 T/a   | PE, PP, PS, PET (PC<15%)           | Melting furnace            | 310                         | ZSM_%                                     | Light oil, kerosene  | 80-90               |
| USS  | 250kg/h    | PE, PP, PS, PET, FRP               | Batch agitator reactor     | 400                         | Al, Ni, Cu                                | C <sub>9</sub> fuel oil  | 80-90               |
| Mitsubishi Heavy Industry                        | 170kg/h    | PP                                 | Melting furnace            | 550                         |   | Light oil  | 95                  |
| Sanyo Engine Company                             | 128kg/h    | PE, PP, PS                         | Melting furnace            | 510-560                     |   |  | 68                  |
| Mitsu Ship Company                               | 24-30t/d   | PE, polymers with molecular weight | Agitator tank              | 420-455                     |   | Fuel oil   | 85                  |
| VEBA Company                                     | 40000t/a   | Polyolefins                        | Hydrogenation reactor      |                             | Lignite                                   | Fuel oil   |                     |
| BP Company                                       | 20kg/h     | PS, PET                            | Sand flow-bed reactor      | 400-600                     |   | petrochemicals   |                     |
| Japan Physics and Chemistry Research Institution | 300 t/d    | Thermoplastic polymers             | Melting furnace            | 2 phases: 200-250 & 360-450 | Al, Ni, Cu, etc                           | Gasoline, kerosene   |                     |
| BASF Company                                     |            | PVC<5%                             | Melting furnace            | 400-500                     |   | Fuel oil, fuel gas, α-olefins  | 90                  |
| Mazda Company                                    | 2kg/batch  | PE, PP, PS, PU, ABS                | Electric furnace           | 400-500                     | AlCl <sub>3</sub> , ZrCl <sub>4</sub> etc | Gasoline, kerosene   |                     |
| Hamburg University                               | 80-240kg/d | PE, PS, PVC                        | Flow-bed reactor           | 640-840                     |   | Aromatics  |                     |
| Hamburg University                               |            | PE, PS, PVC                        | Molten salt reactor        | 600-800                     |   | Aromatics  |                     |
| Hunan University                                 | 1t/h       | Waste plastics, heavy oil          | Flow-bed reactor           | 430-450                     | YNN, silica-alumina/P, PA zeolite         | Gasoline, kerosene   | 75-80               |
| Amoco Company                                    |            | PE, PP, PS                         | Melting furnace            |                             |   | Hydrocarbons   | China Likun Company |
| China Likun Company                              |            | PE, PP, PS                         |                            |                             |   | Gasoline, kerosene   |                     |
| Pyrolysis-gasification Technology                |            | Waste plastics, water              | Pyrolysis-gasifier chamber | 350-600                     | Sand                                      | CO, CO <sub>2</sub> , H <sub>2</sub> , CH <sub>4</sub> , gaseous alkanes & alkenes |                     |

### 7.5 Major Factors Influencing Plastic Pyrolysis

Temperature, catalyst, pressure, presence of air and nature of the plastic components influence both pyrolysis process and product quality. Hence, temperature variations depend on the plastic component and expected product composition. Insulation is required to maintain optimum temperature ranges for pyrolysis (Table 7.3).

Table 7.3 Temperature ranges for optimum pyrolysis of waste plastics

| Temperature (°C)   | Effect  | Main products  |
|--|---|--|
| ≥ 600  | Favours gaseous products & light weight hydrocarbons                            | H <sub>2</sub> , CH <sub>4</sub> & other light weight C <sub>x</sub> H <sub>y</sub> (C <sub>1</sub> -C <sub>4</sub> )                                      |
| 400 - 600  | Favours wax and liquid fuels  | Naphtha, heavy oil, gasoline, diesel oil & kerosene e.g. PP gives fuel oil & gas<br>PS gives styrene monomers & light weight C <sub>x</sub> H <sub>y</sub> |
| 200 - 300  | In catalyst with increased reaction rates favours production of liquid products |  |
| <i>Remarks: Temperature should be ≤1000°C to prevent formation of various NO<sub>x</sub></i> |   |  |

### 7.5.1 Evaluating the Cost-effectiveness of Pyrolysis of Waste Plastics

Table 7.4 Heat balance in the industrial pyrolysis of plastic waste

| Input  | MJ/kg bale | Output                     | MJ/kg bale |
|--|------------|----------------------------|------------|
| Enthalpy of waste plastics                   | 33.5       | Heating value of oils      | 27.2       |
| Electric power                               | 11.3       | Heating value of off gases | 8.6        |
| Fuel   | 8.8        | Heating value of residue   | 3.1        |
| Total  | 53.6       | Total                      | 38.9       |
| Energy balance (Energy lost): 14.7MJ/kg bale |            |                            |            |

(Source: Adapted from Okuwaki et al., 2006)

In some plastic waste pyrolysis technologies (Table 7.4), approximately 11% of output is used for feedstock recycling; 88% is used for energy recovery and 1% is released as waste. However, 60.5% of output is thermally used in plant, 38.5% is shipped out of plant and 1.0% is wasted energy. Consequently, total input over output gives 72.6% which represents the total energy efficiency of the plant.

### 7.5.2 Energy Recovery Potential from Plastic Waste

The pyrolysis of waste plastics with collection of condensate followed by the distillate gives about 99% of combustible compounds and 1% of HCl (Table 7.5). The combustion of the hot pyrolysis-syn gas mixture releases enormous amounts of heat with energy recovery of about 95-99%. Advantages of this technology include:

- Offers an affordable technology with internal-energy-recycling
- Requires minimum feedstock preparation, transportation and distribution



- Technology offers a win-win situation for the environment, energy production and economy

Table 7.5 Percentage energy recovery potential from plastic waste

| Output applications        | Yield (wt%) | Applications of components that can be burned                          | Recovery potential |
|----------------------------|-------------|--|--------------------|
| Distilled light oils       | 20.0        | Fuel furnace & incineration plants                                     | Energy recovery    |
| Distilled light oil (rest) | 11.0        | Feedstock recycling in petroleum refinery plants                       |                    |
| Distilled medium oil       | 4.5         | Fuel for boiler in outside factory                                     |                    |
| Distilled heavy oil        | 21.0        | Fuel for cogeneration in plant   |                    |
| Distilled heavy oil (rest) | 5.5         | Fuel for boiler in outside plant                                       |                    |
| Pyrolysis residue          | 17.5        | Supplementary fuel for outside sludge incinerator                      |                    |
| Off gas                    | 19.5        | Burned in incinerator and recovered as steam in the exhaust gas boiler |                    |
| Hydrochloric acid (HCl)    | 1.0         | Waste water after neutralization                                       | Waste              |

(Okuwaki et al. 2006)

### 7.6 Problems of Recycling Facilities Mitigated

Most waste recycling facilities including incineration plant require high technology due to their complexity. Cost related challenges that have been mitigated through the construction of the PG system include:

- Minimizes the complex designing and planning processes that involve many experts including engineers, politicians, managers etc
- Reduced procedures for operation planning, permits, licensing and discharges certification
- Construction takes limited time, cost and land area
- Risks to surroundings is very low due to the small scale and high safety conditions of plants
- Operation does not require very high technical staff and equipment
- Post closure monitoring or after care requires no specialist skills and cost

Although small use of PG technology meets all above criteria, large scale application may require a varied extent of detail and severity. Ensuring high quality of the material used for construction of PG chamber and regular checks against perforation will minimise any risk of explosion.

### 7.6.1 Introducing Alternative Energy in Developing Country Economies

Fuel wood accounts for about 60-80% of domestic energy requirements in developing countries. Although solar energy production is an alternative, it is intermittent with optimal usage possible within few hours of each day. Cost of heating obtained from direct combustion of biomass varies widely depending on fuel type, availability, burning system technology and socioeconomic desirability. Although biogas economy is generally viewed as dependent on the animal and agriculture production, mixed organic waste can produce efficient burning fuels. In Adopting alternative energy depends on the suitability which includes:

- Suitability of application to environmental, socioeconomic and cultural realities
- Existing research, technology and ability for continuous innovative improvement
- Possibility for local manufacturing with economic access to maintenance services

### 7.6.2 Strengths and Weaknesses of Pyrolysis and Gasification Processes

Table 7.6 Comparing the strengths and weaknesses of the PG technology

| Strengths  | Weaknesses   |
|--|--|
| Not incineration!!   | May suffer from the same negative perception as incineration                 |
| Qualifies for the renewable obligation for a substantial proportion of the feedstock processed | May require extensive waste treatment to remove PVC in mixed MSW             |
| Efficient electricity generation by direct combustion of hot gas in engines                    | Unproven technology on large commercial scale application on MSW             |
| High potential of recycling large proportion of residue waste                                  | System is sensitive to temperature than moving grate incineration technology |
| High temperature makes the system more flexible for varied waste streams                       | More expensive with low cost effectiveness especially for fuel preparation   |
| Acceptable smaller units form part of an integrated system                                     |  |

Due to the relatively unproven performance of these new waste treatment technologies and a false perception of pyrolysis and gasification to be 'incineration by another name' these technologies require real world application. Such application will form the basis of

education and awareness programs. Cost-effective management of the technology with marketing of energy and services will help to improve public acceptability. Table 7.6 evaluates the strengths and weaknesses of the PG technology underscoring the need for continuous improvement.

### 7.6.3 Determining Pollution Impacts of the Residue Ashes

Ash residue samples from the combustion chamber (Sample 1), carbon residue from the pyrolysis gasification chamber (sample 2) and gas delivery pipe (sample 3) and ash residue from normally burned wood as control sample (sample 4) were analysed for presence of heavy metals and other polluting elements and compounds. This was conducted to determine potential environmental impacts of the ash.

Heavy metals and their compounds including dioxins and furans which are hazardous [Annex I waste with properties of annex III of Basel convention (1992)] were generally absent from the ash. Table 7.7 presents the four samples, concentrations (Mass %), tolerance levels for elements and compounds found in the ash and coke residues. Compounds and element identified by # are considered hazardous requiring treatment before disposal as soil supplements. However, their concentrations are below acceptable thresholds.

Table 7.7 Elementary and compound analysis of ash and coke residue

| Substance                          | Sample 1    |              | Sample 2      |              | Sample 3    |              | Sample 4    |              | SOLL     |
|------------------------------------|-------------|--------------|---------------|--------------|-------------|--------------|-------------|--------------|----------|
|                                    | A           | B            | A             | B            | A           | B            | A           | B            |          |
| Na                                 | 0.41        | 0.005        | <i>nn</i>     | <i>0.005</i> | 0.42        | 0.004        | 0.02        | 0.006        | 0.09     |
| MgO                                | 3.23        | 0.008        | <i>nn</i>     | <i>0.008</i> | 0.48        | 0.003        | 1.28        | 0.006        | 6.70     |
| Al <sub>2</sub> O <sub>3</sub>     | 3.01        | 0.004        | 0.89          | <i>0.005</i> | 2.00        | 0.003        | 0.71        | 0.002        | 6.79     |
| SiO <sub>2</sub>                   | 11.12       | 0.011        | 4.65          | <i>0.012</i> | 9.70        | 0.008        | 4.17        | 0.006        | 35.79    |
| P <sub>2</sub> O <sub>5</sub>      | 2.13        | 0.003        | 0.18          | <i>0.004</i> | 0.50        | 0.001        | 1.13        | 0.002        | 0.06     |
| SO <sub>3</sub>                    | 0.95        | 0.002        | 0.04          | <i>0.004</i> | 0.48        | 0.001        | 0.66        | 0.002        | 0.43     |
| <b>Cl</b>                          | <b>1.95</b> | <b>0.002</b> | <b>0.18</b>   | <b>0.001</b> | <b>2.00</b> | <b>0.001</b> | <b>0.47</b> | <b>0.001</b> | <b>#</b> |
| K <sub>2</sub> O                   | 4.50        | 0.007        | <i>0.04</i>   | <i>0.005</i> | 0.37        | 0.002        | 2.84        | 0.003        | 0.51     |
| CaO                                | 16.24       | 0.013        | <i>0.47</i>   | <i>0.005</i> | 3.81        | 0.005        | 9.92        | 0.006        | 20.90    |
| TiO <sub>2</sub>                   | 0.59        | 0.002        | <i>0.12</i>   | <i>0.002</i> | 1.74        | 0.002        | 0.11        | 0.001        | 0.35     |
| <b>Cr<sub>2</sub>O<sub>3</sub></b> | <b>0.02</b> | <b>0.001</b> | <b>0.05</b>   | <b>0.002</b> | <b>0.01</b> | <b>0.002</b> | <b>nn</b>   | <b>0.001</b> | <b>#</b> |
| Mn <sub>2</sub> O <sub>3</sub>     | 1.67        | 0.002        | <i>0.69</i>   | <i>0.003</i> | 0.04        | 0.002        | 1.56        | 0.001        | 0.11     |
| Fe <sub>2</sub> O <sub>3</sub>     | 10.49       | 0.005        | <i>107.44</i> | <i>0.038</i> | 3.99        | 0.002        | 0.49        | 0.001        | 6.32     |
| <b>Cu</b>                          | <b>0.04</b> | <b>0.001</b> | <b>0.07</b>   | <b>0.002</b> | <b>0.05</b> | <b>0.002</b> | <b>0.01</b> | <b>0.001</b> | <b>#</b> |
| <b>Zn</b>                          | <b>0.27</b> | <b>0.001</b> | <b>0.06</b>   | <b>0.003</b> | <b>1.10</b> | <b>0.001</b> | <b>0.03</b> | <b>0.001</b> | <b>#</b> |
| <b>Br</b>                          | <b>0.01</b> | <b>0.003</b> | <b>1.41</b>   | <b>0.025</b> | <b>nn</b>   | <b>0.001</b> | <b>nn</b>   | <b>0.001</b> | <b>#</b> |

However, hazardous components with their tolerance range found in the residue samples include: Chromium compounds (0.001-0.002), copper (0.001-0.002), zinc (0.001-0.003), halogens as chlorine (0.001-0.003) and bromine (0.001-0.025) [Table 7.6]. The tolerance levels are very low compared to recommended threshold values meaning adequate ash amounts could be used as soil supplements. Applying the ash to farm land should be done after a soil and ash quantitative and qualitative analysis.

#### **7.6.4 Transportation and Handling of Plastic Waste**

Densification of the plastic waste or high calorific value waste to obtain PEF by pelletizing reduces feedstock making transportation and handling easier. Shredding and volume reduction by compaction ensure consistent heating value and loading into PG chamber. This may increase labour cost while reducing feedstock volume with corresponding transport cost.

## Chapter Eight

### Developing and Optimizing the Pyrolysis-Gasification Technology

#### 8.0 Developing a Multiple Problem-solving Invention

The invention and use of the PG technology solves an energy production and waste disposal problems in a way that hones environmental, technological, health and socioeconomic benefits. Such simple, affordable, cost-effective and scalable technology is developed to transform waste plastics to heat which can be used directly or transferred to electricity. Figure 8.1 presents the technological sketch where plastic waste (A) is loaded into the pyrolysis-gasification chamber (C) with water drops (B) that is heated by burning charcoal in combustion chamber (G) to produce the pyrolysis-syn gas (D). D is transmitted into the combustion chamber through multilayer metal pipe (F).

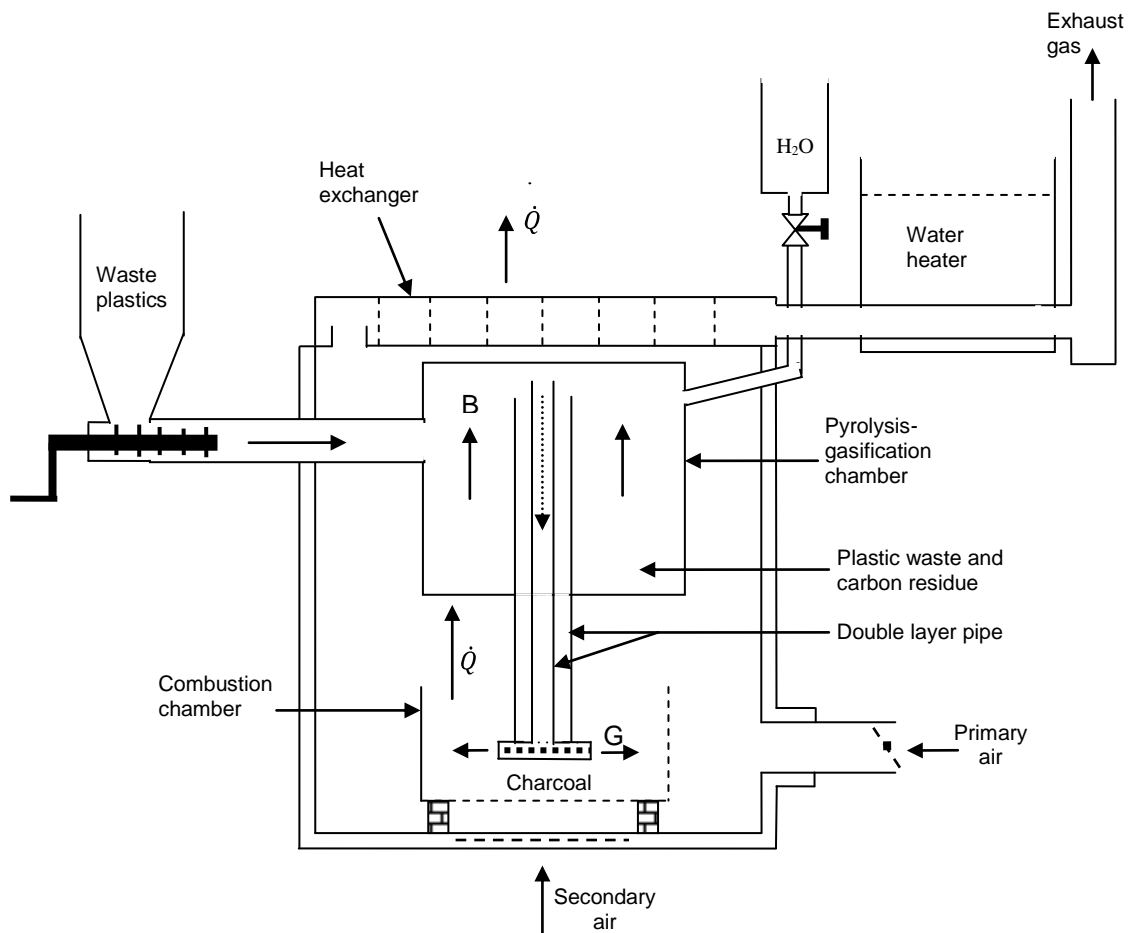


Figure 8.1 Optimised design of the PG technology

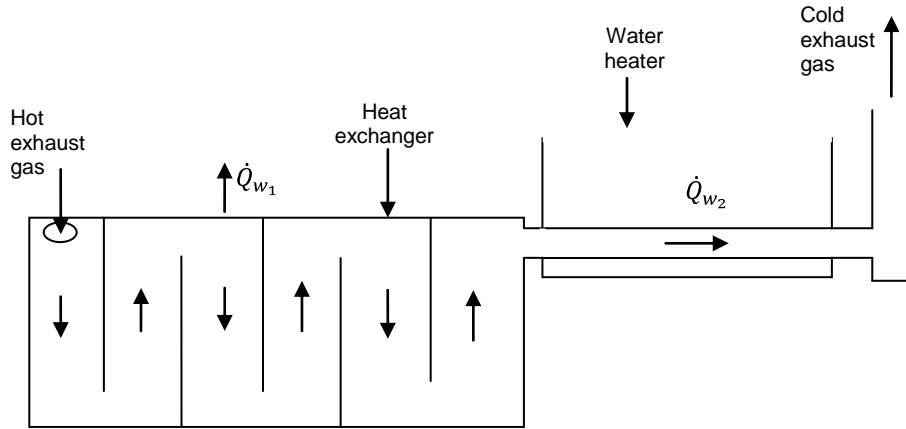


Figure 8.2 Use of heat exchangers and water heater

Using temperature of hot exhaust gas ( $t_{G_1}$ ) entering the heat exchanger (Fig. 8.2) transferring ( $Q_{w_1}$ ) and exiting at ( $t_{G_2}$ ) into water heater transferring ( $Q_{w_2}$ ) to exit at ( $t_{G_3}$ ) to atmosphere, rate of heat transfer is calculated (Eq. 8.1). The energy recovery efficiency depends on heat production ( $\dot{Q}_W$ ) and recovery rates ( $\dot{Q}_{w_1}$  and  $\dot{Q}_{w_2}$ ) as illustrated by figure 8.2. Various heat exchangers involving parallel-flow, counter-flow, cross-flow, multipass and mixed-flow recuperators could be adapted to demand. Heat recovered:

$$\dot{Q}_W = \dot{Q}_{w_1} + \dot{Q}_{w_2} = \dot{m}_{w_1} c_w (t_{G_1} - t_{G_2}) + \dot{m}_{w_2} c_w (t_{G_2} - t_{G_3}) \dots \dots \dots 8.1$$

Heat transfer from given surface area:

Applying Fourier's law of conduction to calculate the rate of heat transfer ( $\dot{Q}$ ) per unit area (A) of wall surface for metal with thermal conductivity ( $\lambda$ ) and thickness (x) within a temperature range  $t_{G_1}$  and  $t_{G_2}$  where  $t_{G_1} \square t_{G_2}$ ) is given by equation....:

$$\dot{Q} = -\frac{\lambda A}{x} (t_2 - t_1) = \frac{\lambda A}{x} (t_{G_1} - t_{G_2}) \dots \dots \dots 8.2$$

Heat transfer depends on the rate of cooling determined by Newton's law of cooling:

$$\dot{Q} = \alpha A (t_{G_1} - t_{G_2}) \dots \dots \dots 8.3$$

Where  $\alpha$  is heat transfer coefficient given in  $W/m^2 K$  or  $kW/m^2 K$ .

Heat exchanger effectiveness ( $\epsilon$ ) is the ratio of the actual heat transferred to the maximum possible heat transferred neglecting any heat losses to surroundings (Eq. 8.3). For heat exchanger with mass flow rate for hot ( $\dot{m}_h$ ) exhaust gas with specific capacities ( $c_h$ ) and temperature change of ( $t_{G_1} - t_{G_2}$ ) for heat exchanger and ( $t_{G_2} - t_{G_3}$ ) for water heater respectively (Eq. 8.4):

$$\dot{Q}_w = \dot{m}_h c_h (t_{G_1} - t_{G_2}) + \dot{m}_h c_h (t_{G_2} - t_3) \dots \dots \dots 8.4$$

For the hot water heater with heat exchanger exhaust gas of mass flow rate for hot ( $\dot{m}_h$ ) and cold ( $\dot{m}_c$ ) water with specific capacities ( $c_h$  and  $c_c$ ) and overall temperature changes of  $(t_{hi} - t_{he})$  and  $(t_{ce} - t_{ci})$ , where i and e refer to inlet and exit respectively:

$$\dot{Q} = \dot{m}_h c_h (t_{hi} - t_{he}) = \dot{m}_c c_c (t_{ce} - t_{ci}) \dots \dots \dots 8.5$$

$$\dot{Q} = C_h (t_{hi} - t_{he}) = C_c (t_{ce} - t_{ci}) \dots \dots \dots 8.6$$

Where  $\dot{m}_h c_h = C_h$  and  $\dot{m}_c c_c = C_c$  are thermal capacities of hot and cold fluids

Since fluid with smaller thermal capacity ( $C_{min}$ ) will attend the maximum temperature change of  $(t_{Hmax} - t_{Cmin})$ , where

$$\varepsilon = \frac{\dot{Q}}{C_{min}(t_2 - t_1)} \dots \dots \dots 8.7$$

Well-designed heat exchanger should achieve maximum temperature change of one of the fluids for a given driving force for given logarithmic mean temperature difference ( $\Delta \bar{t}_{ln}$ ) known as the number of thermal capacity ( $N_{tu}$ ).

$$N_{tu} = \frac{\text{Temperature change of one fluid}}{\Delta \bar{t}_{ln}} \dots \dots \dots 8.8$$

For the hot (h) and cold (c) fluids:

$$N_{tu_h} = \frac{t_{hi} - t_{he}}{\Delta \bar{t}_{ln}} \dots \dots \dots 8.9$$

$$N_{tu_c} = \frac{t_{ci} - t_{ce}}{\Delta \bar{t}_{ln}} \dots \dots \dots 8.10$$

Defining  $N_{tu}$  more generally give:

$$N_{tu} = \frac{\text{greater of the 2 fluid temperature differences}}{\Delta \bar{t}_{ln}} \dots \dots \dots 8.11$$

Energy recovery in the PG technology is enhanced by the integration of a heat exchanger and a water heating reservoir with exhaust gas being the energy carrier.

### 8.1 Pyrolysis and Gasification as Emerging Thermal Treatment Technologies

Heating organic materials in waste under pressure and absence or limited amount of air produces combustible gases. Although pyrolysis and gasification is applicable to over 50 feed stocks, they are best suited for dried sewage sludge, wood, mixed plastics from

WEEE scrap, household and commercial (packaging) wastes, agricultural and forestry residues, tyres and any other organic waste.

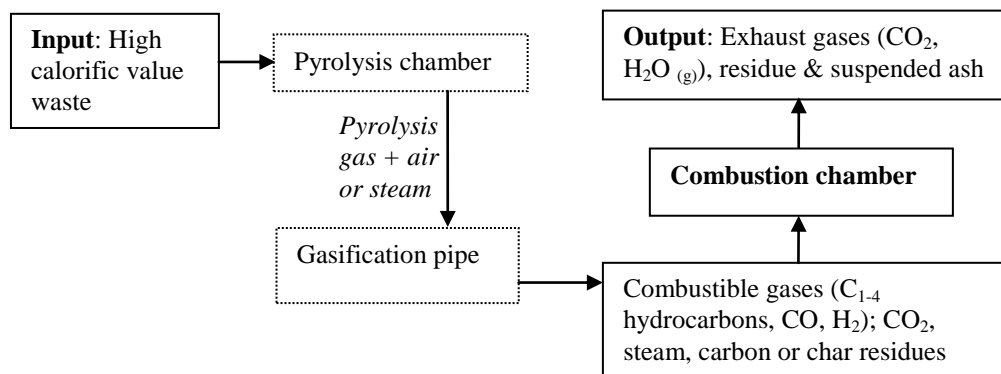


Figure 8.3 Major inputs and outputs of a typical PG process

Figure 8.3 shows a schematic representation of inputs and outputs of a typical pyrolysis and gasification process. The moist waste plastic is pushed into the PG chamber where it is heated to melt and pyrolyse. In the absence of moisture in feedstock, water droplets are introduced into the PG chamber to form steam, creating turbulence and increasing chamber pressure. The steam and pyrolysis gas mixture is forced by the internal pressure rise through a temperature barrier into the combustion chamber.

### 8.1.1 Role of the Decreasing Temperature Barrier

Due to slight temperature drop, heavier organic molecules resulting from the free radical cleavages can recombine forming heavier molecules which fall back to the PG chamber for re-fragmentation. Only the lighter molecules overcome the temperature barrier to enter the gasification pipe. This gas mixture flows downwards through an increasing temperature zone with further cracking before entering the combustion chamber. Conditions favouring the optimal production of the combustible gases ( $C_1$ - $C_4$  hydrocarbons, CO,  $CO_2$  and  $H_2$ ) and release of residue carbon are:

- High residence time which is influenced by the gas flow rate and pipe length
- Turbulence and mixing of the pyrolysis gas, air and/steam mixture
- Quantity of the pyrolysis gas emitted and the speed of flow through an increasing temperature gradient into the combustion chamber

### 8.1.2 Role of the Combustion Chamber

The combustion chamber is loaded with burning charcoal or wood to produce initial energy to the process. Combustion is optimized by air-gas mixing to enhance efficient



energy production (Fig. 8.4). Special characteristics of the combustion chamber relevant to achieving this goal are:

- The chamber has 3 perforated walls and bottom to enhance air in-flow and mixing
- There is perpendicular convergence of in-coming primary and secondary air flowing in opposite direction to the emerging pyrolysis-syn gas mixture
- The pyrolysis-synthesis gas emerges into the burning charcoal and burns in-situ with the flames and hot gas flowing through the burning charcoal before getting into the chimney

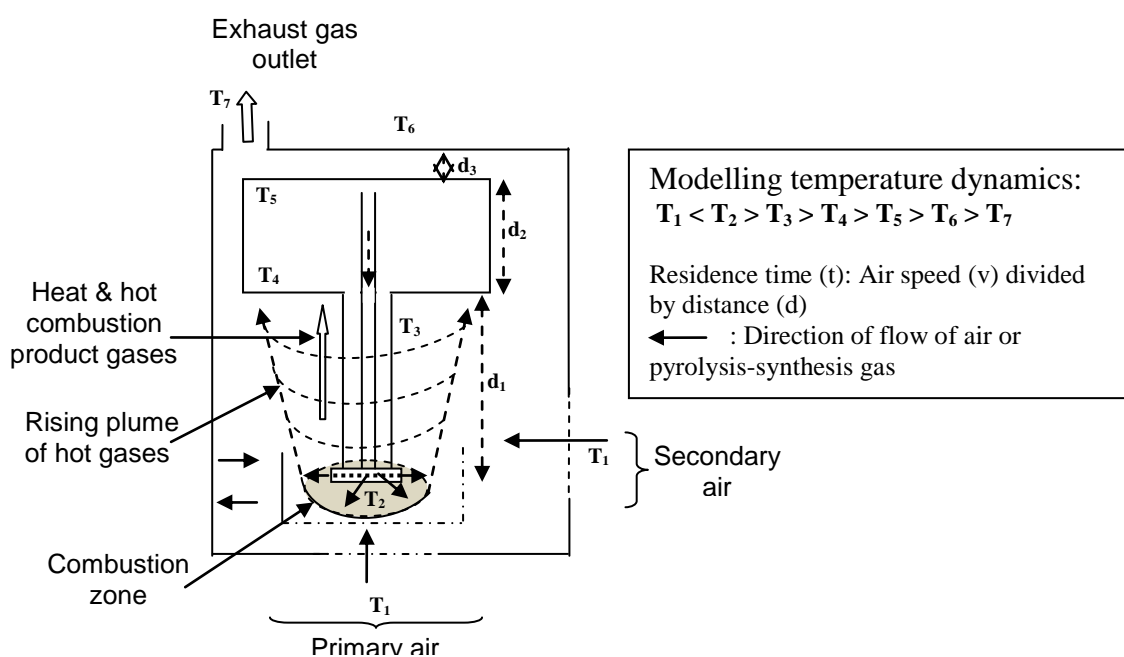


Figure 8.4 Temperature profile within the pyrolysis-gasification system

- Inlet primary and secondary air flows into the combustion chamber and exits only through the chimney.

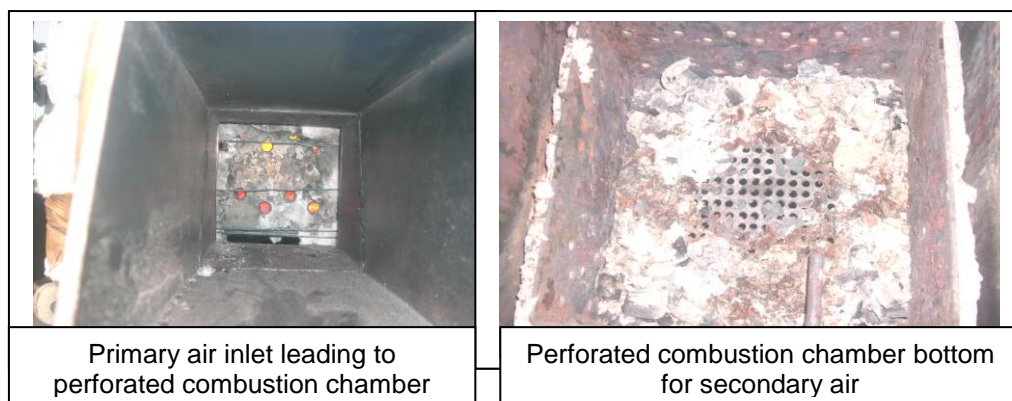


Figure 8.5 Set-up to enhance air mixing and exit from PG technology

Figure 8.5 presents the temperature distribution within the pyrolysis gasification technology system. Temperature variation within the system causes the continuous production of the pyrolysis-synthesis gases, free expansion and throttling enhancing system kinetic energy and gas mixing.

The combustion chamber is designed to enhance thorough air-gas mixing with significant retention time for effective burning (Fig. 8.6). Burning under glowing charcoal gives opportunity for the metallic oxides from the charcoal to scavenge all acid gases. The exhaust gases flow out into the atmosphere with suspended ash being deposited at bottom of the chimney.

The unresisted one-directional flow of air from surroundings and gas-steam mixture from PG chamber to combustion chamber and release through the chimney of exhaust gases are all temperature driven. This is illustrated below:

1. Creation of the temperature barrier between  $T_4$  and  $T_5$  ( $T_4 < T_5$ ) as heat release and heat production temperature poles respectively. A wider temperature barrier favours lighter gas particles to cross the barrier leading better the combustion efficiency.
2. The rising temperature gasification region (pipe) from  $T_5$  to  $T_2$  has particle residence time defined as the time for the particle to move through distance (D) where:

$$D = 2d_2 + d_1 \dots\dots\dots(1)$$

### 8.1.3 Combustion of Pyrolysis-synthesis Gas in Charcoal

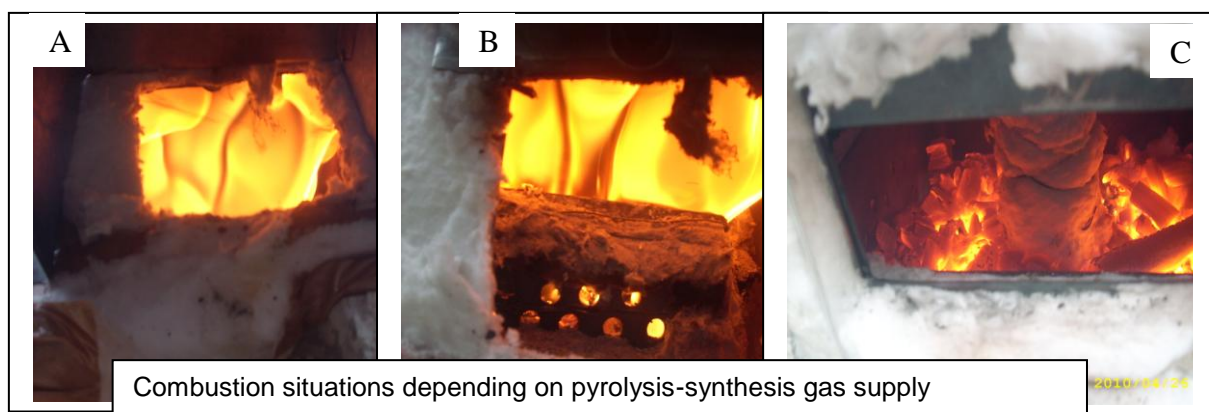


Figure 8.6 Flame size and combustion depends on pyrolysis-synthesis gas supply

3. The temperature difference between  $T_2$  and  $T_8$  ( $T_8 < T_2$ ) determines the heat lost through exhaust gases i.e. the higher the temperature difference the better the need to recycle exhaust gases to recover some of the heat
4. Although  $d_1$  and  $d_2$  need to be adjusted to scale of the PG plant,  $d_1$  should always be minimized while  $d_2$  is maximized

Figure 8.6 shows the combustion chamber with burning pyrolysis-synthesis gas in charcoal at various stages depending on the rate of production of the pyrolysis-synthesis gas. The combustion is efficient with no unburned organic inflammable gases escaping through this combustion zone. Very high gas productions rate at higher temperatures were observed. Equally, the flame volume increases with higher gas production rate leading to a corresponding rise in temperature and turbulence.

Figure 8.6 justifies the reason for the complete absence of VOCs in the exhaust gases compared to incineration, since no organic molecules can escape through the combustion chamber unburned. The flame volume is proportional to the gas production rate it chases the gas ensuring complete oxidation.

#### 8.1.4 Plastic Feedstock and Charcoal Residue

The main energy production inputs are plastic feedstock and charcoal. Charcoal produces initial energy for the pyrolysis of plastics, serves as the ignition source for any pyrolysis-synthesis gas, scavenges acidic gases by metallic oxides (e.g. CaO) and captures for burning any tiny solid carbon particles.

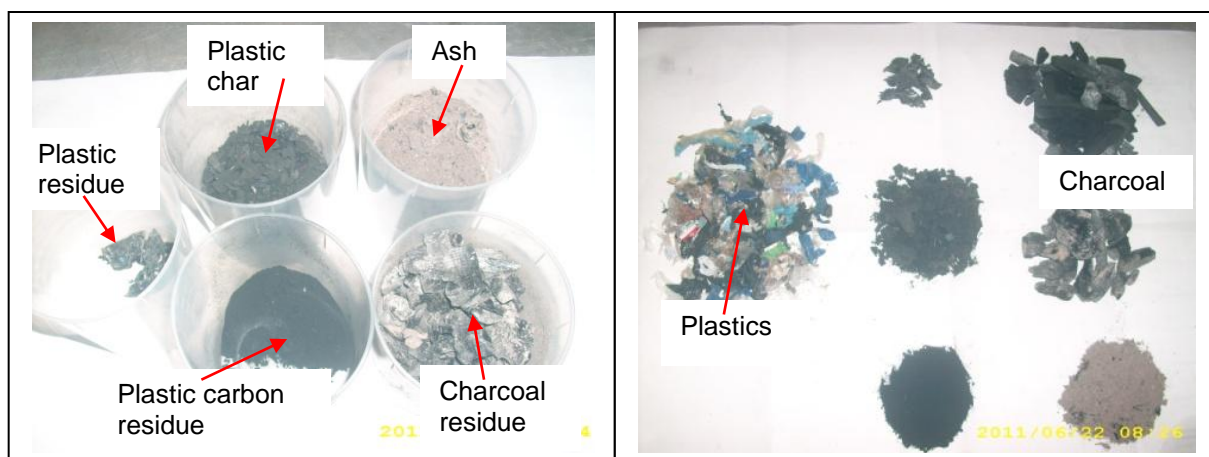


Figure 8.7 Comparison of initial, intermediate and residual material

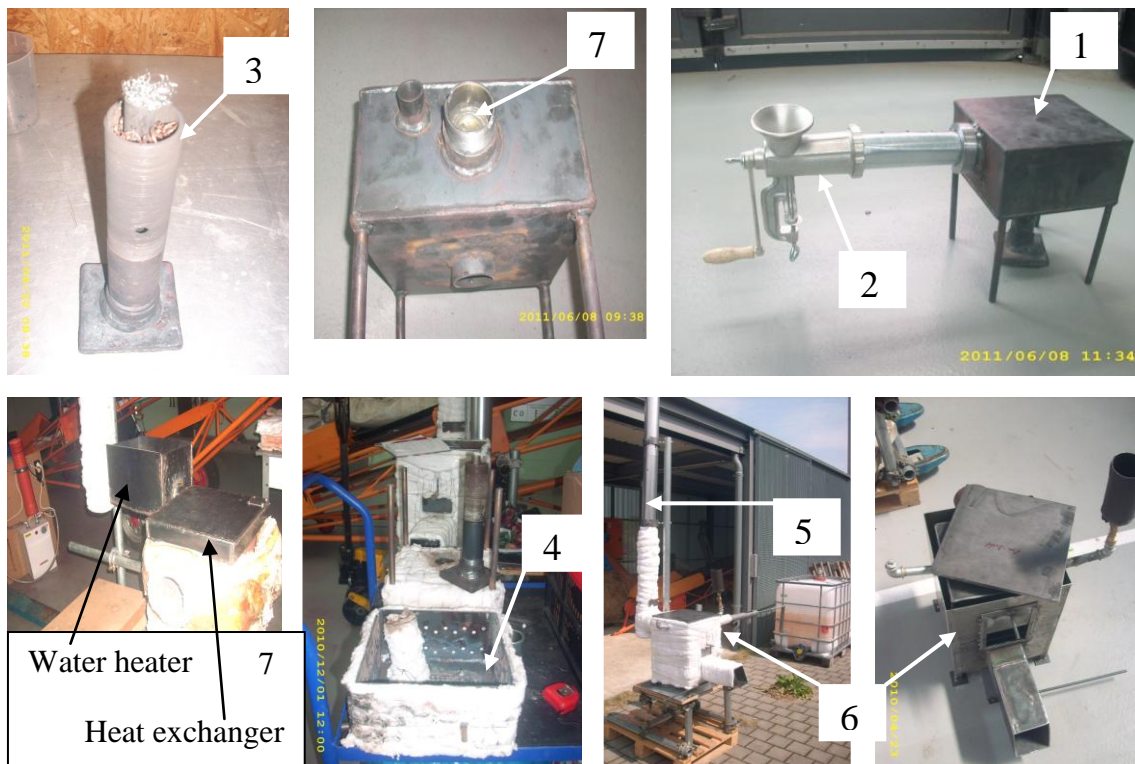
The charcoal burns effectively to produce ash which after cooling could be screened for disposal. Residue charcoal can be reused in subsequent heat production applications.

Figure 8.7 presents the plastic residues (plastic char samples, plastic carbon residue, including melted but not charred plastics recovered from the PG chamber) and charcoal and its residue ash.

## 8.2 Description of PG Technology Components

This technology possesses few components (Fig. 8.8) for easy maintenance and handling especially in low technological societies. The seven main components are:

1. *PG chamber* made of iron of 4-5mm thickness carries the plastic waste loader, gas transmission pipes, water inlet for steam production and a safety vent
2. *Plastic waste* is driven by a rotating normal shifting or spiral screw ensuring consistent loading
3. *Concentric multiple layer transmission pipes* providing increased residence time for gas mixture flowing into combustion chamber
4. *Combustion chamber* offers efficient gas-air mixing leading to in-situ gas combustion and uni-directional flow of exhaust gases based on natural draft



1: Pyrolysis-gasification chamber; 2: "Fleische wolf" or adapted spiral loader; 3: External layer of the double layer pyrolysis-synthesis gas transmission pipe; 4: Combustion chamber; 5: Chimney; and 6: Insulated and uninsulated casing of the PG technology; 7 heat exchanger and water heater

**Figure 8.8** Description of the important components of the PG Technology



5. *Chimney* extending into the atmosphere prevents indoor pollution and improves natural draft
6. *Insulation* reduces rapid heat losses, stabilizes system temperature with internal heat recycling to maintain energy self-sustenance
7. *Heat exchanger and water heater* improving heat recovery and energy-use efficiency

Gas leakage within the PG system is easily ignited and burned with the flame maintained until gas production stops (Fig. 8.9). Such leakages lead to pressure lost may impair the flow of pyrolysis-syn gas into the combustion chamber.

A safety valve made-up of a lighter metal vent was adapted to the PG chamber. In case of an explosion, the vent will break open releasing its contents into the metal casing. This content will mix with exhaust gases and/ or burn before being released through the chimney.

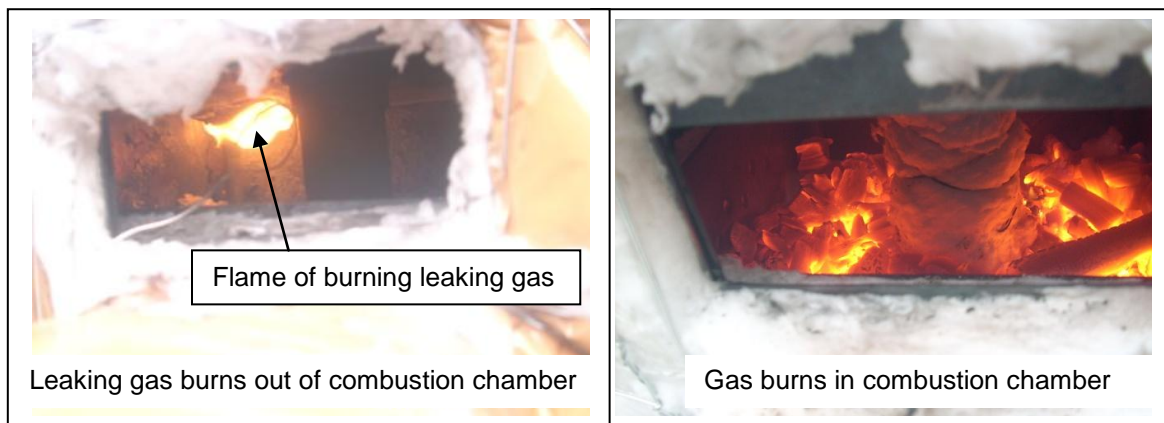


Figure 8.9 Gas leakage is ignited and burned within the casing

Average time for dismantling to clean is 10-20minutes while mounting time is 10-15minutes. Cleaning is estimated to be done depending on size of the technology and usage with the amount of char or carbon deposit in PG chamber being the determinant factor. Ash from charcoal could be removed without dismantling.

### 8.2.1 Rationale for the PG Technology Design

Figure 8.10 presents the impact evaluation process leading to the PG technology development decision. This was necessary to determine the potential acceptability and usability of the technology in a competitive energy market. Various incentives for end-users and developers were identified. Major impacts of the technology at various stages

involving cost-benefits analysis, safety, risk and gender issues including social, economic and environmental concerns were carefully evaluated.

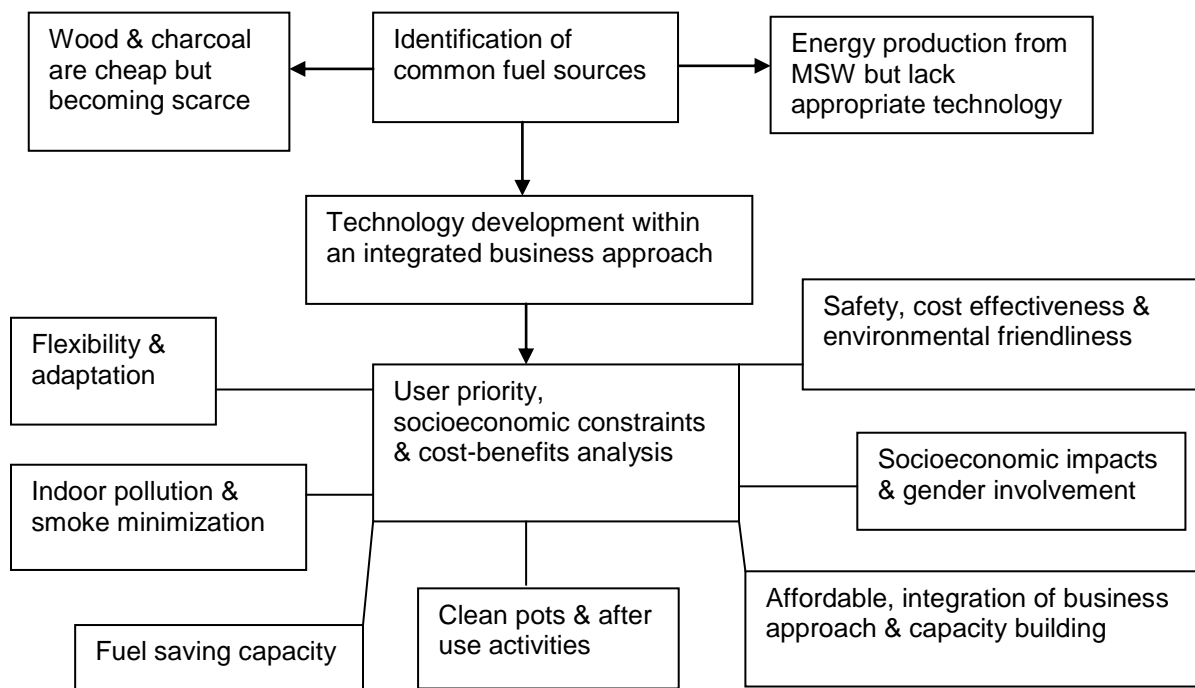


Figure 8.10 Rationale behind the development of the new PG technology

### 8.3 Inventive Process of the PG Technology

Figures 8.11 to 8.23 present highlights of landmark conception, design, construction and modifications stages (A to G) leading to the current optimized PG Technology. The inventive process involved regular testing, monitoring, evaluation and continuous improvement.

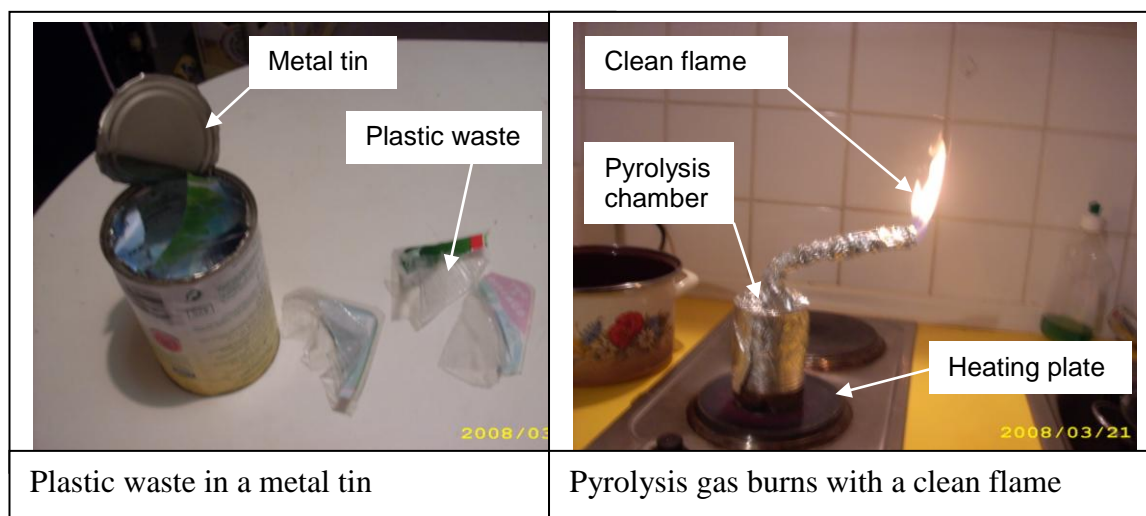


Figure 8.11 Testing of the idea of cracking plastics and burning gases in-situ

- A. The idea of cracking plastic waste and burning the pyrolysis gas in-situ led to using heat from an electric heater to crack some plastic waste and lighting the pyrolysis gas produced. A clean hot blue-yellowish flame was produced with size of flame proportionally varying with rate and amount of gas released (Fig. 8.11). Recycling the heat produced creating a self-sustaining process was possible after using an external initial heat source.
- B. The first technological model with self-sustaining heat-recycling system in which hot gas produced from pyrolysis chamber is transmitted to combustion chamber and burnt in-situ was produced (Fig. 8.12).

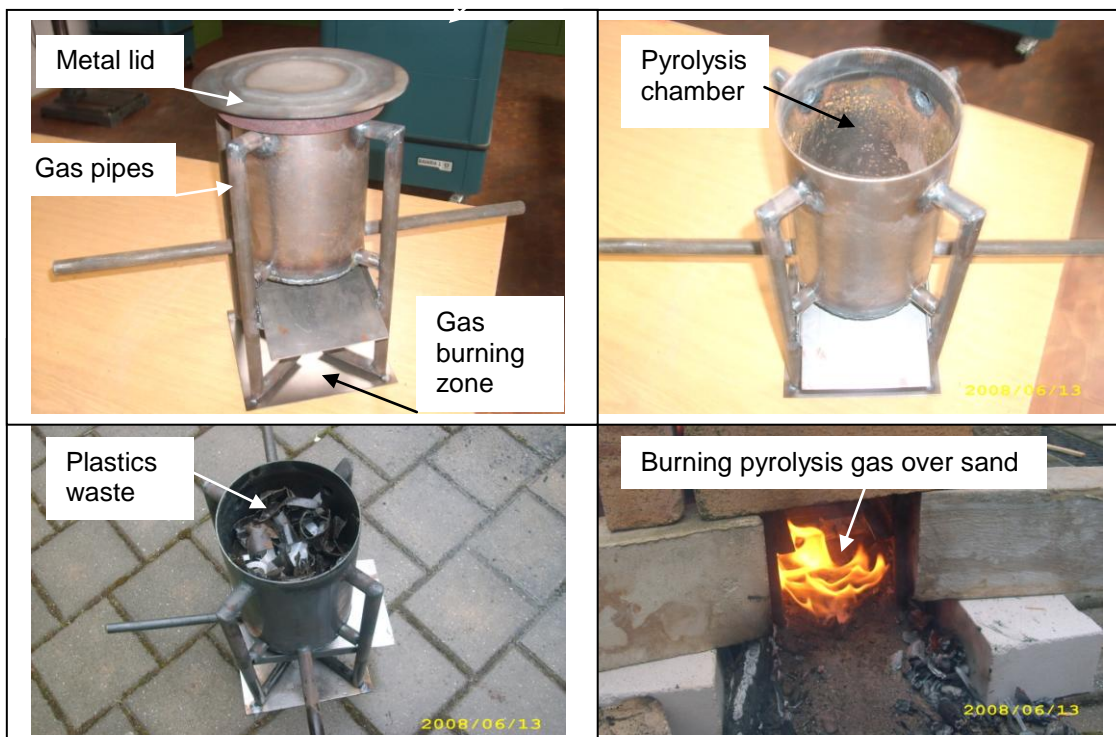


Figure 8.12 Cracking plastics and burning gas in-situ with heat recycled



Figure 8.13 Pyrolysis gas flows to combustion chamber and burns in-situ



Integrated burner with improved gas nozzles in combustion chamber led to improve gas burning (Fig. 8.13). However, gas cooling occurred below the burner and increased pressure in the PG chamber led to leakage of gas through the lid. Gas cooling also resulted in over-flow of condensed pyrolysis gas in the pipe below burner (Fig. 8.14).

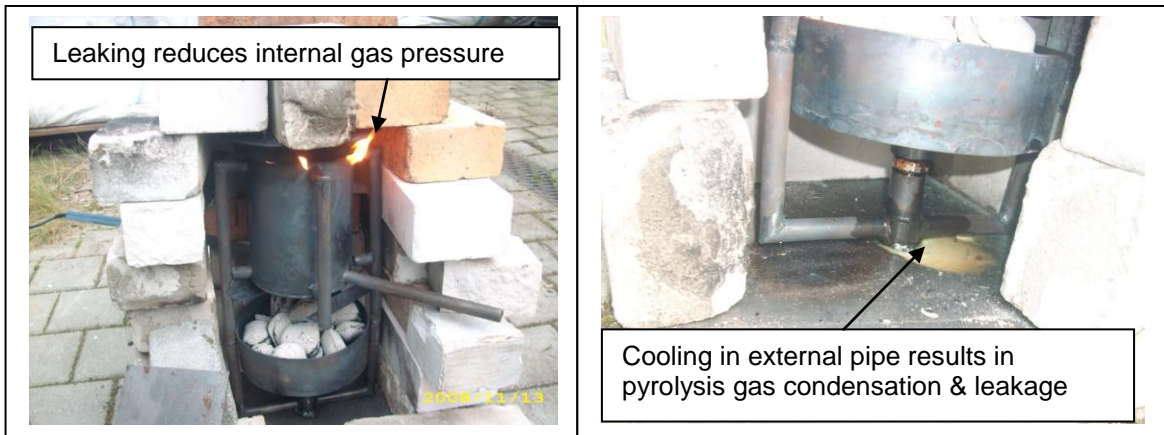


Figure 8.14 Gas leakage from lid and condensation in pipe

C. Second model with insulated enclosed pyrolysis and combustion chambers including gas pipes to reduce temperature losses and cooling (Fig. 8.15).

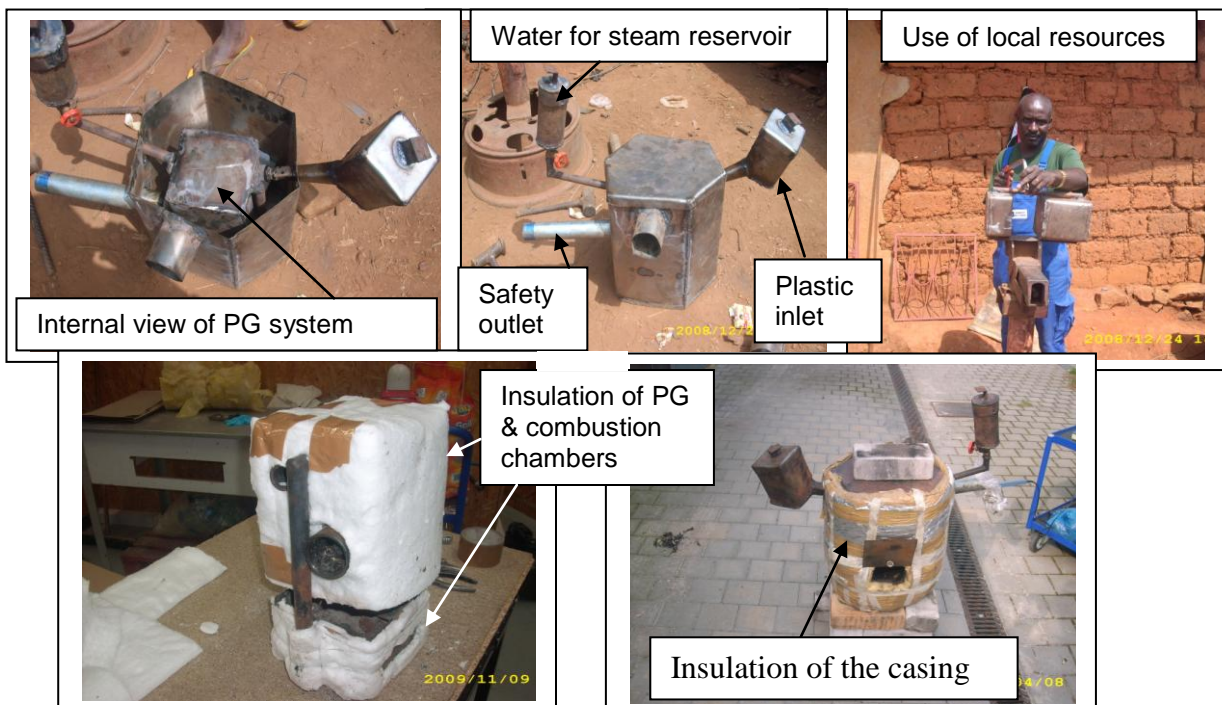


Figure 8.15 Construction and casing of second PG technology model

D. Third model insulated with sand-sawdust-earth mortar enclosed joined pyrolysis chamber to gas release nozzles with enclosed gas conveying pipes (Fig. 8.16).



System has improved temperature control and enhanced continuous plastic loading and steam production.

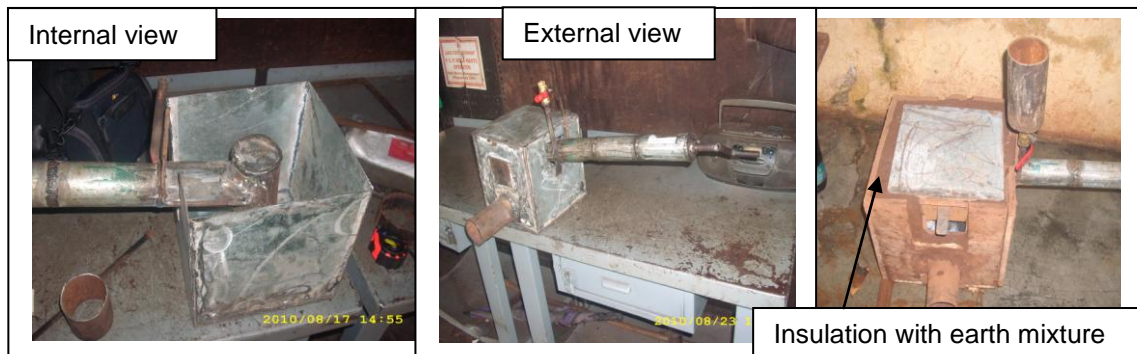


Figure 8.16 Third model with internal piping and earthen layer insulation

E. Fourth model with optimized insulation system using altra wool with application of shifting screw driver adapted to improve continuous plastic loading (Fig. 8.17). Though the shifting screw loading method was effective, returning the screw and reloading took longer time with difficulties in managing loading consistency. Hence the 'fleische wolf' using the spiral screw system ensured continuous and consistent loading.

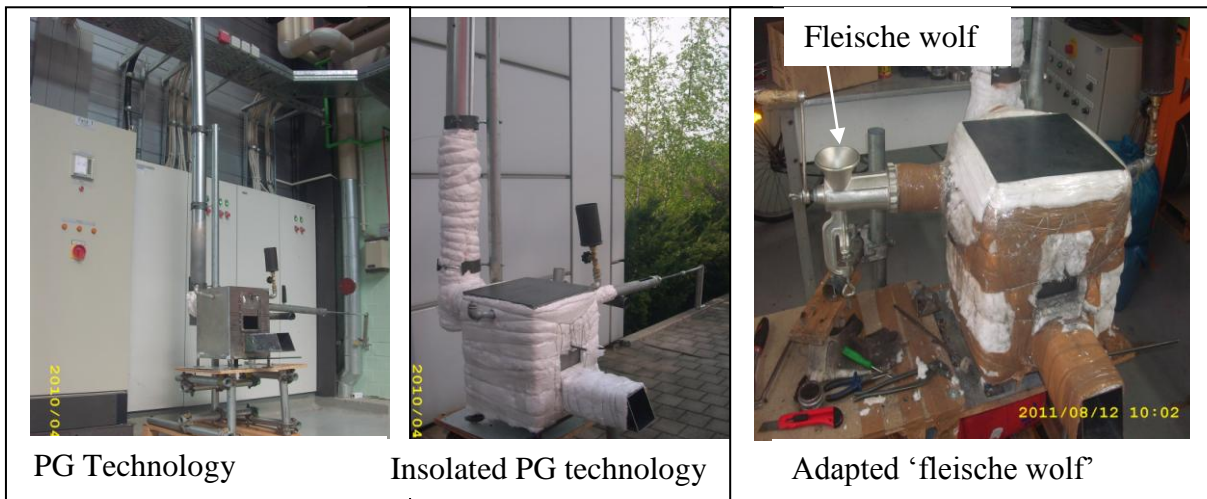


Figure 8.17 Fifth optimized model of the PG technology

F. Adapting and using the 'fleische wolf' was innovative, very cheap (14€) and effective compared to buying a spiral screw loader (Fig. 8.18). The 'Fleische Wolf' is usable for small scale and requires an extension to preventing gas back-flow

G. Construction and adaptation of a continuous screw and spiral loaders compared to the batch wise loading improved the continuous functioning

H. PG chamber insulation improved gas production rate by stabilizing and maintaining the high temperature required.



Figure 8.18 Insulation of PG chamber and external casing

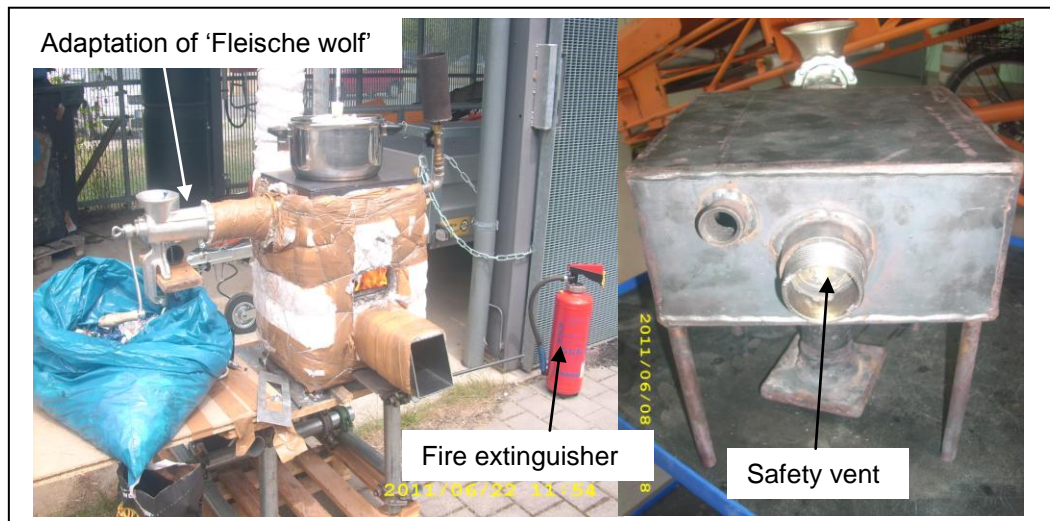


Figure 8.19 Adaptation of the 'Fleische Wolf' and a safety valve

High safety consideration based on risk prevention was given to the construction of the PG technology and experimental exercises. A fire extinguisher was always available during experimental exercises which were duly monitored and conducted outdoors. A

safety valve serving as a vent in the event of a potential explosion was installed on the PG chamber (Fig. 8.19).

#### 8.4 Milestones of the Invention Process and Models

Construction of various models of the PG technology made use of basic hand tools and machines. From each model and various experimental test conducted, problems linked to functioning were evaluated with need assessment and subsequent actions to be taken identified.

Table 8.1 Goals of the inventive process

| Major models   | Reason for modification  | Effects & issuing problems   |
|--|--|--|
| Model 1: The idea  | Thermal recycling of plastic waste by cracking and burning gases in-situ   | Successful process with use of external energy source but needed the recycling of energy produced  |
| Model 2: Pyrolysis chamber with pipes to transmit gas to burner directly below   | <ul style="list-style-type: none"> <li>● To reuse heat produced by burned gases to crack further plastics</li> <li>● To ensure a self-sustained process</li> <li>● To integrate a chimney that improves natural air draft</li> </ul>   | Heat produced by burned gases is recycled heating further plastics but gas transfer leads to cooling and condensation with heat losses; gas out-flow through the lid occurred, and burner air-gas mixing in burner needed improvement  |
| Model 3: Pyrolysis-gasification chamber with pipes to transmit gas to burner directly below inserted into an insulated casing  | To ensure that heat from burned gases is recycled heating further plastics while preventing gas cooling, condensation and out-flow through the lid; and improving burner air-gas mixing and stabilizing oven temperature.  | Goals were achieved but optimal insulation, consistent loading of plastic feedstock, pot-heating surface contact required upgrading  |
| Model 4: Pyrolysis-gasification chamber joined to burner with gas flow through concentric multiple layer temperature barrier with soil mixture insulation            | <ul style="list-style-type: none"> <li>● Insulating to reduce heat losses using local materials stabilizes system temperature</li> <li>● Design and construction of continuous feeding screw loader to enhance feedstock loading consistency</li> </ul>  | Temperature stabilizes and loading improves but with low consistency and efficiency. There is compaction at loader-pyrolysis chamber high-low temperature interface region leading to spontaneous over-loading in pyrolysis chamber  |
| Model 5: Pyrolysis-gasification chamber linked with concentric multiple layer gas transmission pipes to burner with gas flow through increasing temperature gradient | <ul style="list-style-type: none"> <li>● To insulate oven and gas transmission pipe while improving heat conduction to pyrolysis-gasification chamber</li> <li>● Gas flow through hotter zone increases gas fraction, resident time, turbulence and mixing</li> <li>● Gas release through tiny holes improves mixing with primary and secondary air enhancing combustion efficiency</li> </ul> | The entire PGT provides a cost-effective, safe and self-sustained environmentally friendly technology for thermal plastic waste recycling with clean energy recovery. However, the engineering, mass and energy balance, efficient energy use and entire system efficiency requires further modelling and optimization in larger scale application |

The proposed corrective actions from each experiment were conducted stepwise. The expected effects from the corrective action were evaluated vis-à-vis overall goals of the



entire invention process (Table 8.1). These processes were repeated continuous with various modifications until model 5 with integration of the heat exchanger and water heater presented with main features in figure 8.20 was achieves with exhaust gas samples collected and analysed.

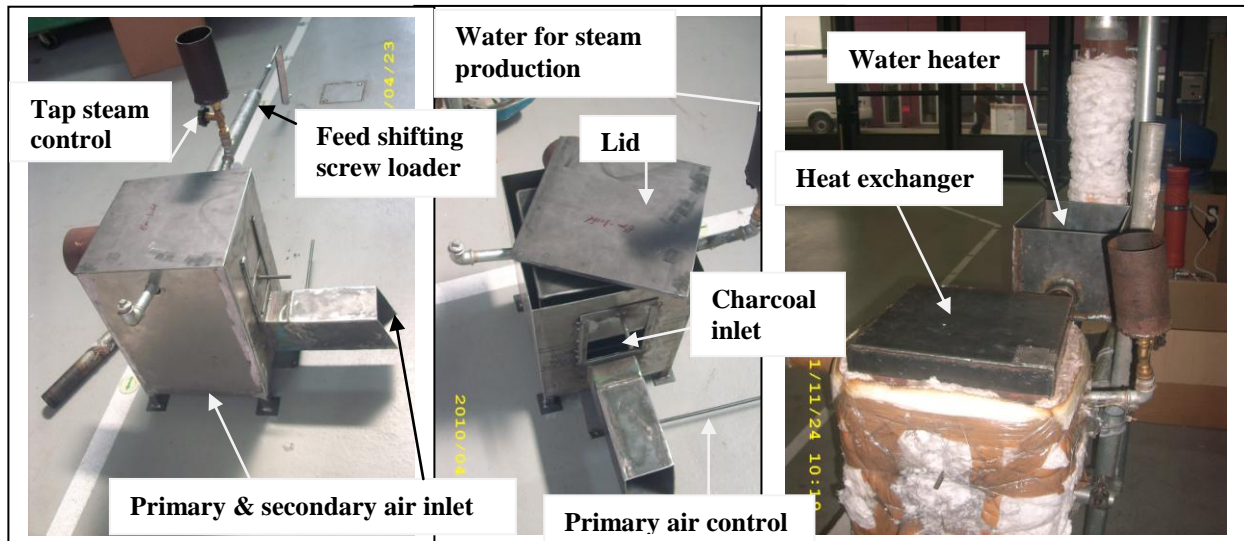


Figure 8.20 Structural features of the PG technology

A design of the technology was prepared followed by construction and optimization of various models. Various experimental exercises involving monitoring and evaluating results to improve the technological function and efficiency were conducted leading to the final design, construction and testing of the optimized invention.

#### 8.4.1 Construction of the PG Technology at LAWMA

The construction using local material bought and others selected from the scrap waste metal at the LAWMA maintenance workshop involved some significant modification compared to the previous designs and constructions carried out in Cameroon and Germany. In order to harness heat ( $Q$ ) and concentrate it around the pyrolysis-gasification chamber, a double layered concentric metal pipe system was adopted (Figures 8.21).

This system increases gas-flow-distance and resident time for pyrolysis-steam mixture ( $D$ ) within a high-increasing temperature region which enhances syn-gas ( $G$ ) production. The PG chamber is made smaller to reduce excess accumulation of plastics improving the pyrolysis and gas generation process.

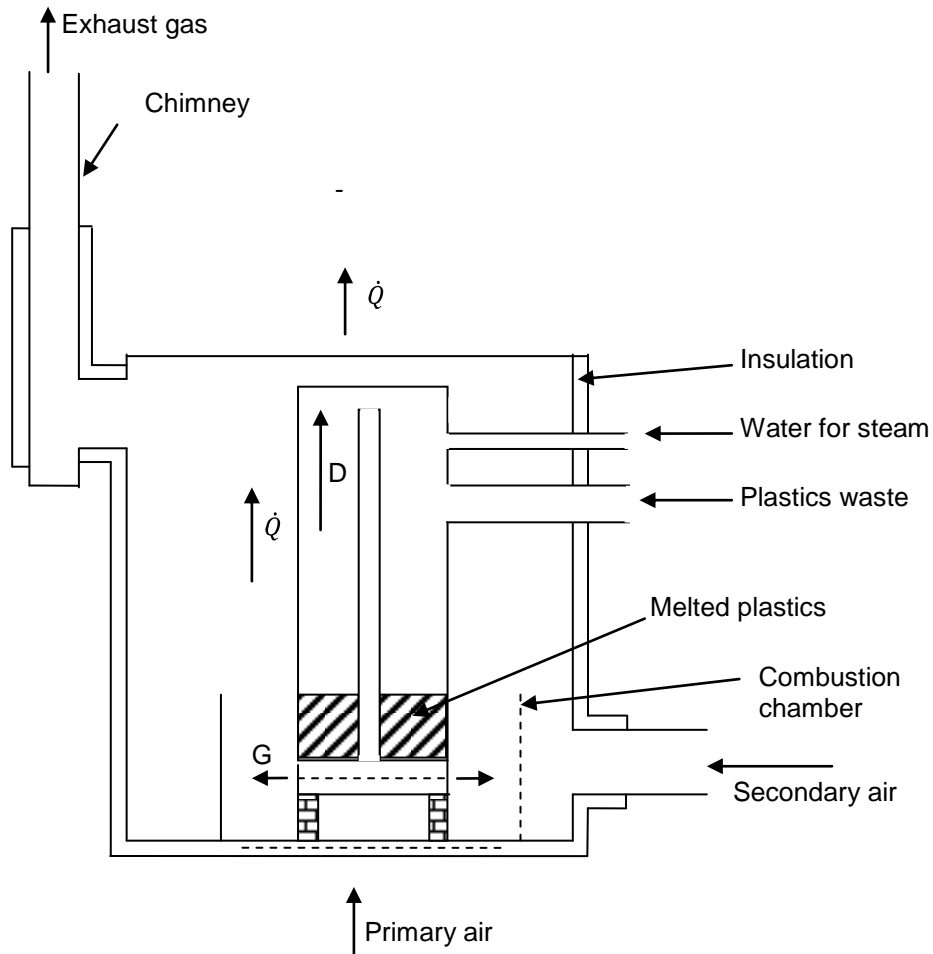


Figure 8.21 Optimised design of the PG technology

Advantages of the design include:

- Cooling of the pyrolysis-syn gas mixture as it moves from PG to combustion chambers is minimized due to flow from lower into higher temperature zones. This results in continuous cracking and improved gasification
- PG chamber envelopes the pyrolysis-syn gas conductor pipe minimizing influences of external temperature fluctuation
- Pyrolysis-syn gas mixture flows from the PG chamber toward a cooler medium where only the light gas fraction overcomes the cooling barrier. On crossing this zone, heavier molecules return to the PG chamber for further cracking.
- The convergence of the in-flowing primary and secondary air in perpendicular direction against a counter-flow of exiting pyrolysis-syn gas mixture enhances gas-air mixing (turbulence) leading to improved burning

- This design minimizes the use of construction material, labour, time and cost (Fig. 22). However, the quality was lowered compared to construction made in Germany.



Figure 8.22 Construction of optimised PG technology in Lagos, Nigeria

#### 8.4.2 Temperature Control and Insulation Using Modern Materials

Various insulation materials were used to insulate the following parts:

- PG chamber and gas transmission pipes
- Lower part of the chimney
- Metal casing (oven)

The materials used for insulation were the glass wool (burned at higher temperature), earth-sand-sawdust mixture (considerably good insulation) and the Alsitra wool. Insulation using Alsitra (Aluminium silicate content from 48-54% in melting process) and Altra (Aluminium oxide content of 72%, 80%, 97% produced from the sol-gel process) composed of wool, mats, stampings and modules were capable of resisting temperature up to 1650°C. However, with too much air space between hot casing and surrounding the insulation is not very efficient leading to significant heat losses.

#### 8.4.3 Insulation with Local and Modern Insulation Materials

A wooden box as casing with a 2cm thick insulation layer (cavity) between the wood and the metal casing was prepared. A homogenous mixture of sand, soil, water and sawdust was carefully mixed into a paste and loaded into the cavity and left to slowly dry under shade to avoid cracking (Fig. 8.23). Advantages of using this mixture are:

- Presence of sawdust reduces density of insulation layer minimises weight
- The cavities created by dried saw dust serves as expansion-shock-absorber during heating and cooling

- These materials (sand, saw dust and soil) are cheap and readily available
- Acquisition of the materials and preparation of the mixture demands little cost, labour and time

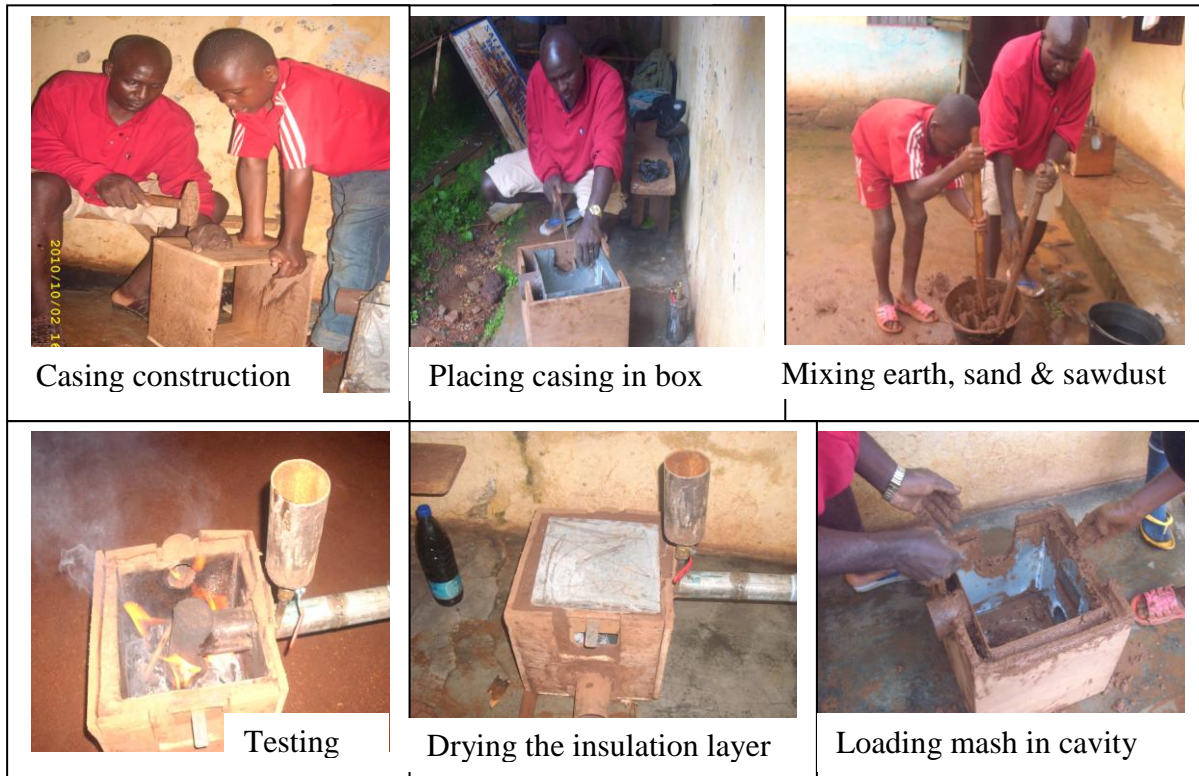


Figure 8.23 Insulation with local materials and testing process

Insulation using local materials is cheap and more effective but increases the weight of the technology making transportation difficult compared to using modern insulation material (Alsitra, Altra or glass wool) which is lighter but expensive. However, the usage of local materials especially ceramics, clay or earth bricks is recommended especially for fixed heat production centres or combined heat power plants.

### 8.5 Experimental Procedure for PG Technology Testing

Relevant information noted during experiments included the date, weights, temperature and time of the action including observable physical environmental conditions (windy, sunshine, cold, snowing, raining etc) in using data forms and tables (appendix III). An evaluation of each experiment deducing measurable objectives and actions for subsequent exercise were noted (Appendix IV) such as:

- Masses of plastic, charcoal and water used, water evaporated and simmered
- Record of essential temperatures and changes necessary for calculating various heat transformations and trends

- Collection of sample exhaust and pyrolysis gases including ash and carbon residues for qualitative and quantitative analysis

### 8.5.1 General Observation of the functioning of PG Technology

Table 8.2 Calculation of the intervening energy forms

| Energy type                             | Symbol   | Formula   | Quantity/ KJ | Energy group |
|---|--|---|--------------|--------------|
| Syn-Pyrolysis gas combustion            | $E_{csg}$  | $m_{pl} \cdot CV_{pl}$                              | 47300.00     | Production   |
| Charcoal combustion                     | $E_{hcc}$  | $m_c \cdot CV_c$                                    | 19240.00     |              |
| PGT & casing                            | $E_{hsc}$  | $m_{cs} \cdot c_{iron} \cdot \Delta T$              | 2454.00      | Storage      |
| Heating pot to 100°C                    | $E_{hp}$   | $m_p \cdot c_{Al} \cdot \Delta T$                   | 65.52        |              |
| Heating water to boil                   | $E_{cp}$   | $m_w \cdot c_w \cdot \Delta T$                      | 1145.00      |              |
| Heating plastics to melting point       | $E_{lhp}$  | $m_{pl} \cdot c_{pl} \cdot \Delta T$                | 422.50       | Usage        |
| Latent heat of vapourisation for water  | $E_{hwp}$  | $m_w \cdot L_w$                                     | 2257.00      |              |
| Heat lost through exhaust gases         | $E_{aeg}$  | $V_a \cdot \rho_a \cdot A \cdot c_c \cdot \Delta T$ | 10.82        |              |
| Energy consumption efficiency ( $E_e$ ) | $\frac{E_{hsc} + E_{hp} + E_{cp} + E_{lhp} + E_{hwp} + E_{aeg}}{E_{csg} + E_{hcc}} \times 100\%$ |   |              |              |

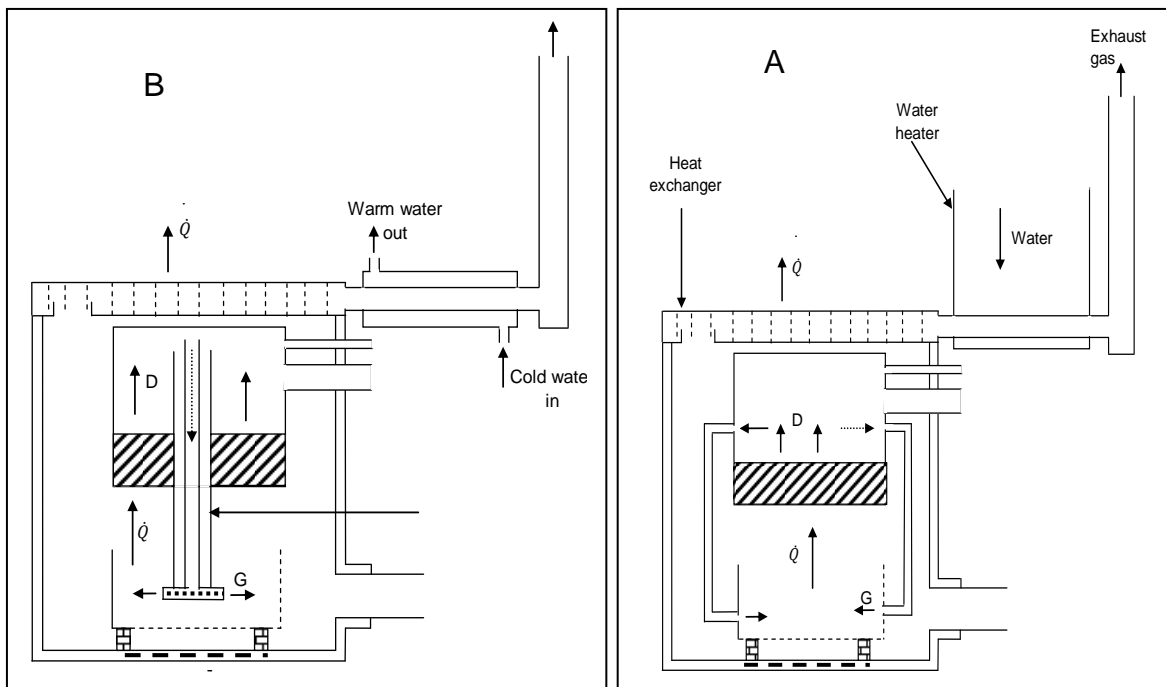


Figure 8.24 Comparing slight modification in the optimised models A and B



Fitting the data obtained into the equations in table 8.2, the energy quantities were calculated with respect to production, storage, usage and lost. The energy calculations were combined to estimate energy production and consumption efficiency. Slight modifications can cause significant impact on technology functioning.

Table 8.3 compares the most recommended models designated as A and B. However, based on the factors outlined, it can be concluded that model B is preferred to A. However, if the insulation of the entire technology is efficient to maintain an almost constant high temperature within the system, both models will function similarly.

Figure 8.24 show the design of the optimized model A with double gas pipes and B with single double layer gas pipe connecting the PG and combustion chambers. In B pyrolysis-syn gas cools as it moves through the external pipes compared to A where the gas moves through a central pipe with increasing temperature. B is therefore recommended though both models can be used when internal oven temperature is homogenously high.

### 8.5.2 Characteristics of Appropriate Household Energy Technology

There exist various household energy technologies making use of varied fuels. Major characteristics and principles of appropriate household energy technology (AHET) considered during the development phases of the PG technology include:

- Optimal use of cheap fuel with improved in- and out-door air pollution
- Generation of income for constructors, distributors and fuel (plastics) suppliers

Table 8.3 Principles/factors affecting combustion efficiency

| Characteristics                   | Wood  | Waste plastic  |
|-----------------------------------|---|--|
| Burning                           | Does not burn   | Does not burn  |
| Volatilisation                    | When heated releases volatile gases that burn   | When heated cracks into volatile gases that burn           |
| Optimal condition                 | Time, temperature (650°C), O <sub>2</sub> , turbulence & surface area   | Time, temperature (300-550°C), O <sub>2</sub> , turbulence |
| Combustion products               | CO <sub>2</sub> , water vapour & heat   | CO <sub>2</sub> , water vapour & heat                      |
| Heat production                   | Optimal drying  | Normal drying  |
| Waste produced                    | Smoke, ash & charcoal   | Smoke and char   |
| State of CO <sub>2</sub> & energy | Renewable   | Non-renewable  |
| Remarks                           | Use of plastic waste to replace wood saves the forest which sequesters the non-renewable CO <sub>2</sub> released |  |

- Ability and safety in easy starting, efficient monitoring and proper shot-down
- Application gives access to and involves women (mainly users) and men (mainly producers) with multiple incentives and socioeconomic benefits

Wood and waste plastic composed of organic polymers. These polymers when heated to high temperature release volatile gases which burn readily presence of oxygen to produce heat, CO<sub>2</sub> and water vapour (Table 8.4).

The construction of the PG technology was done in Germany, Cameroon and Nigeria using varied modern and indigenous materials, human labour and technological know-how. Although the optimised model constructed in Germany bears dimensions shown in table 8.5, the technology can be scaled and constructed according to demand, feedstock characteristics and supply.

Table 8.4 PG technology and feedstock specific data

| Item measured                                      | Dimensions (mm)       | Quantity (kg) |
|--|-----------------------|---------------|
| Particle size range of waste plastic               | 50mm to 500mm         | 3.75          |
| Particle size range of shredded plastics           | 5mm to 25mm           | 3.75          |
| Screw-driven loader empty                          | Length: 750mm         | 3.65          |
| Screw-driven loader filled with plastic waste      | Diameter: 45mm        | 3.85          |
| Screw-driven loader well filled with plastic waste |                       | 4.05          |
| Mass of PG chamber                                 | 200mm x 200mm x 15mm  | 6.30          |
| Mass of reactor + 2 water reservoirs               | -----                 | 8.65          |
| Mass of reactor, water & oil reservoirs + loader   | -----                 | 12.30         |
| Heat exchanger                                     | 300mm x 300mm x 50mm  | 10.5          |
| Water heater                                       | 200mm x 200mm x 300mm | 9.55          |

Having constructed the technology in Germany, Cameroon and Nigeria proves that it can be constructed and used in every community by trained technicians. This gives and proves the technology's universal application potential and market.

### 8.5.3 Temperature Control and Management

Measuring and evaluating the internal temperature during various experiments confirms importance insulation in a temperature-driven system. Observations made include:

- Temperature of PG chamber is very sensitive to heating rate and insulation
- Plastic waste feeding and air in-flow rates influence system temperature (cool)
- Consistency of initial energy supply and internal heat conservation is required
- Temperature rise increases production rate of pyrolysis-synthesis gas

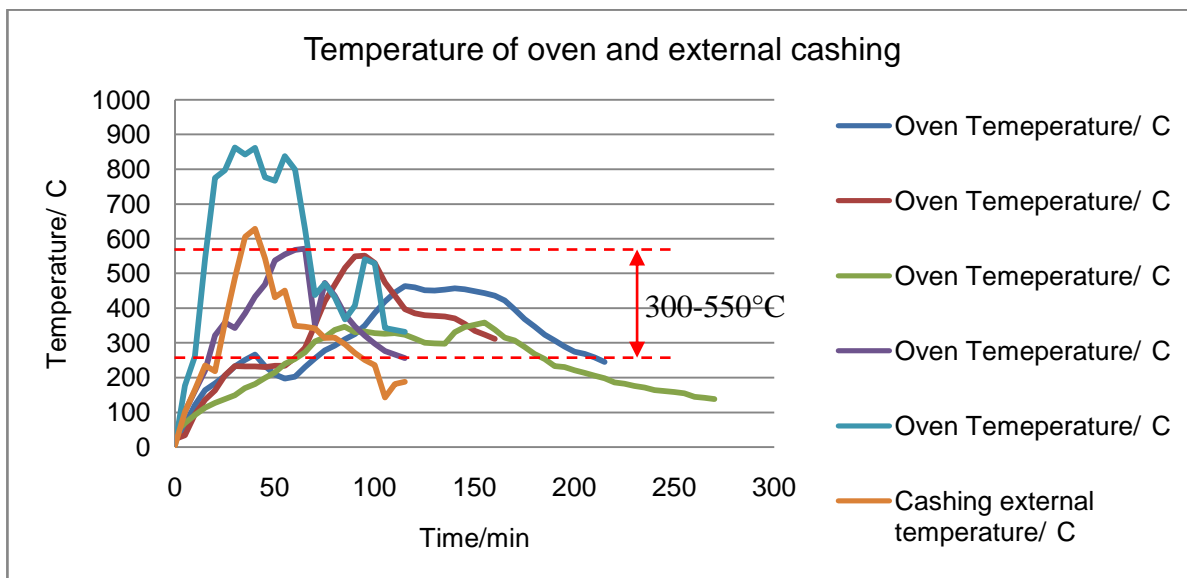


Figure 8.25 Oven temperature variations in PG technology

Figure 8.25 indicate the vulnerability of the oven temperature to surrounding changes. Oven temperature controlled and stabilization is observed to depend on efficient insulation, consistent heating and regular air in-flow and exhaust gas release rates. Due to in adequate insulation, the external casing temperature is observed to be high and fluctuating. However, analysing the oven temperature graphs shows that:

- The optimum average temperature range occurs between 300-550°C
- System temperature depends on the initial energy source, heating consistency and insulation
- Temperature drops gradually during oven cooling with little influence from surrounding temperature

Leakages and burning of pyrolysis-synthesis gas within the PG technological system maintains the temperature and effective system functioning.

#### 8.5.4 Water Heating, Boiling and Simmering Test

Heating water from normal temperature to boiling point (100°C) and simmering in a pot indicates a gradual temperature rise with low sensitivity to oven temperature changes. Temperature of water in pot was observed to be rather sensitive to surrounding temperature variations. Good oven-pot surface contact, efficient insulation of oven walls, good heat storage capacity and effective heat conduction contributes to energy-use efficiency (Fig. 8.26).

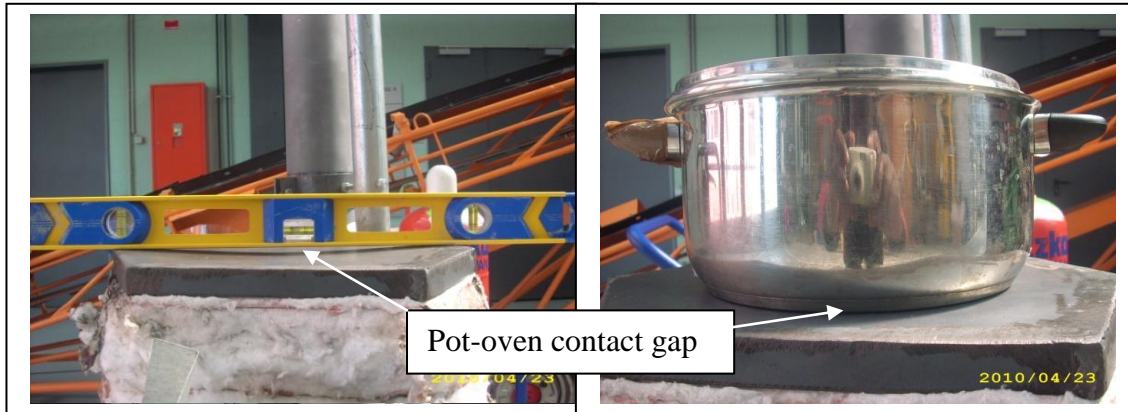


Figure 8.26 Good oven-pot surface contact enhances optimal heat transfer

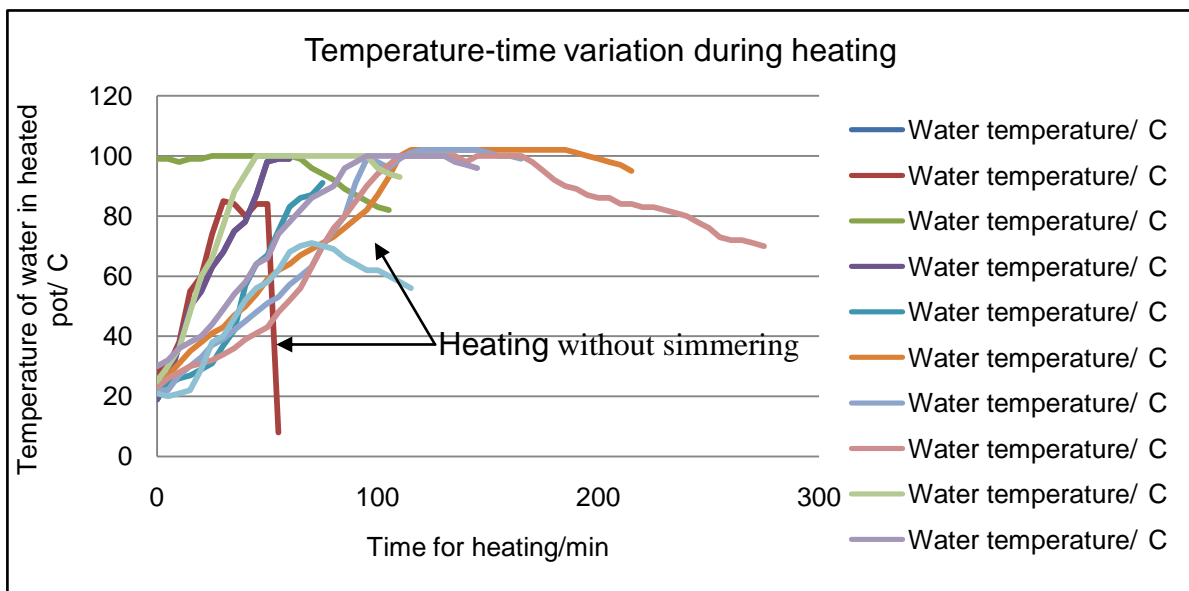


Figure 8.27 Temperature-time variations for water heating, boiling and simmering

- Once boiling starts oven system temperature variation affects water boiling very slightly and slowly
- The PG technology functioning can be assessed based on its ability to heat and boil water which is the basis of its domestic and industrial application

When water starts to boil simmering continues for relatively long time even without further gas production and burning (Fig. 8.27) until cooling begins. The cooling process indicates that after the use of high level heat and low value heat during cooling can be applied to drying and pasteurisation e.g. it took about 100minutes for the water temperature to drop from 100°C to 70°C. Hence the gradual temperature rise before

water boiling starts is due to high heat accumulation. If the system is well insulated, cooling will be slower even after heating stops.

### 8.5.5 Water Boiling and Simmering Test

Figure 8.28 presents the temperature-time variations for optimized PG technology. It proves the consistency of water temperature rise to boiling, simmering and cooling. Though the oven temperature fluctuates significantly, there is a continuous temperature rise within the heating zone (A), stabilization zone (B) involving phase change zone and decreasing temperature or cooling zone(C).

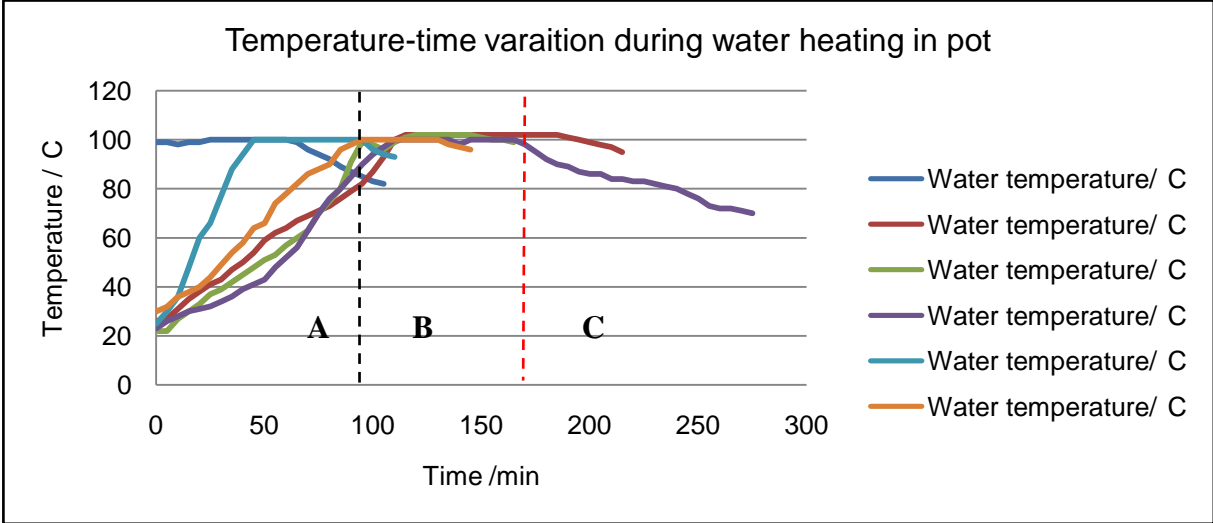


Figure 8.28 Temperature-time variations for water heating, boiling and simmering

The positive gentle gradient in temperature as shown in figure 8.28 within the heating zone is due to:

- Pot-oven contact is not very symmetrical i.e. the lack of uniform contact creates an air layer between the two surfaces. Such deformation of iron on heating is prevented by using cast iron.
- Air in-flow through primary and secondary inlets depends on the movement of surrounding air
- Position within the oven cavity for measuring temperature varies

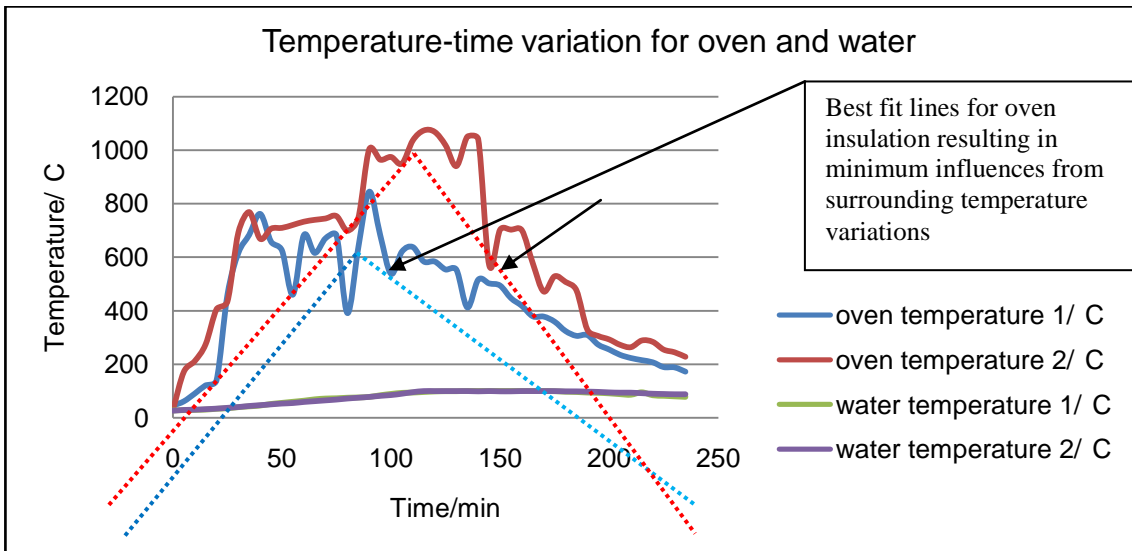


Figure 8.29 Temperature-time variations for PG technology and water

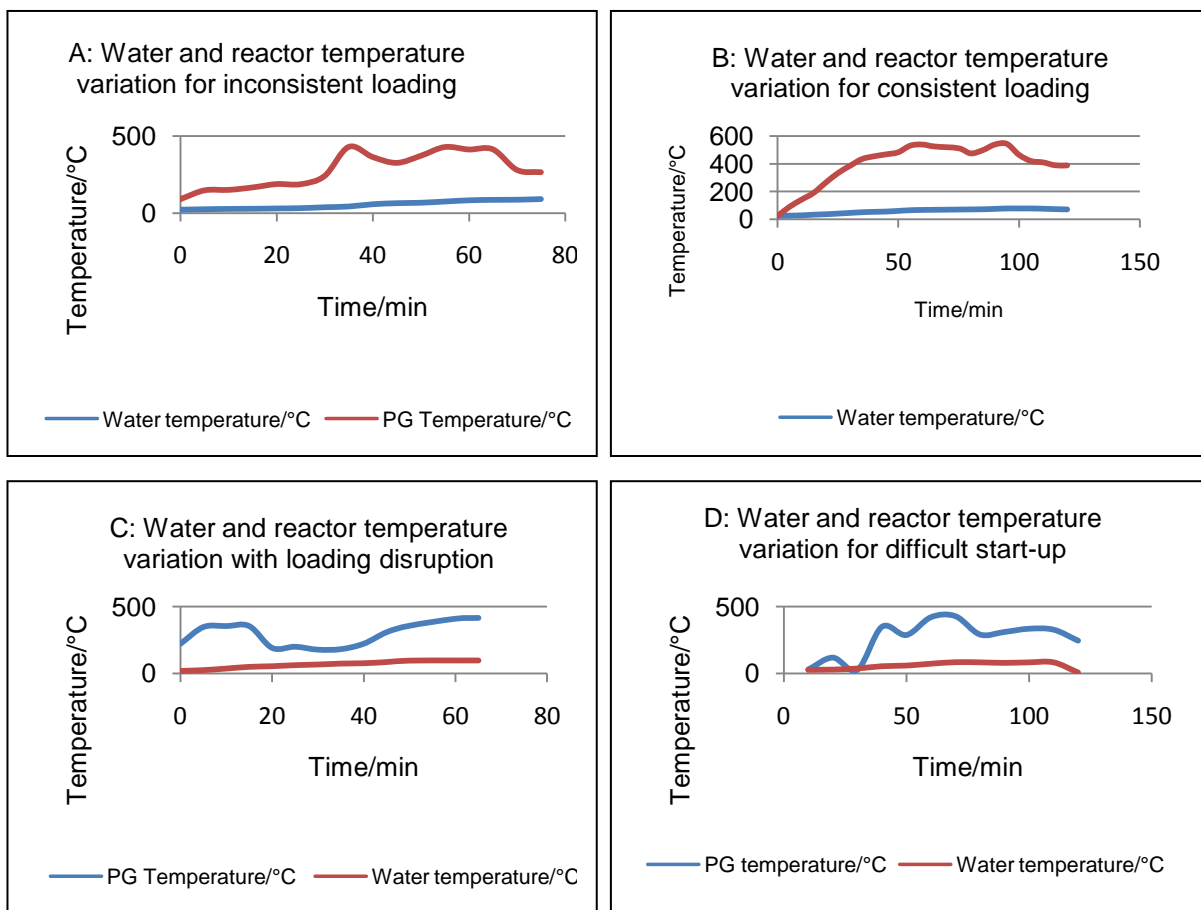


Figure 8.30 Water and pyrolysis-gasification chamber (oven) temperature variations

General observations on the oven temperature trends:

- The temperature rises gradually depending on the heating rate to a peak value and falls gradually based on the cooling rate. This implies that good insulation

and effective control of plastic loading with resultant gas production rate and air in-flow can keep the oven temperature high for as long as required.

- Maintaining the oven temperature range between 400-800°C is best for effective functioning of the PG technology, since water temperature rise is not very sensitive to that of the oven (Fig. 8.29).
- Waiting time for water to boil can be reduce by improving oven-pot contact, covering pot and reducing surfaces by which heat is lost from the pot.
- The higher the peak temperature of the oven the higher the cooling rate of the oven. Hence, keeping the oven temperature lower reduces heat losses due to cooling (Fig. 8.30).

### 8.5.6 Effect of Heat Recovery on Functioning of the PG Technology

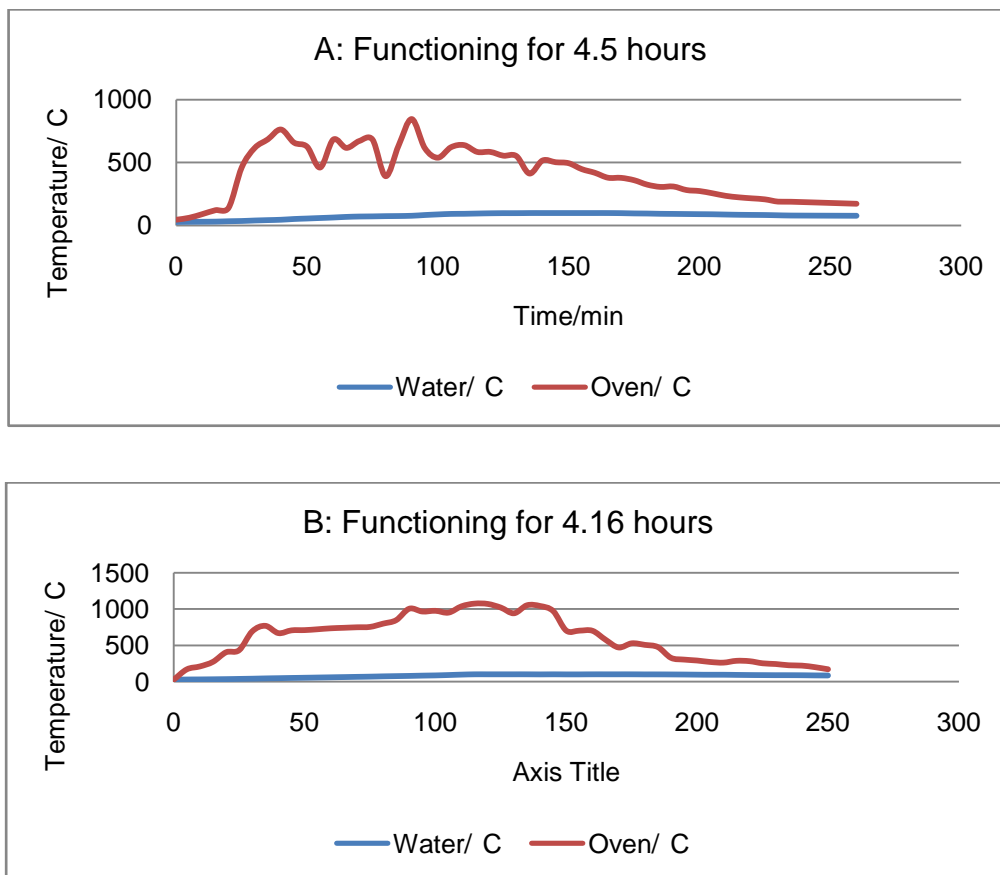


Figure 8.31 Oven and water temperature variations for extended durations

The effective functioning of the PG technology with good insulation presents an oven and water heating, boiling and simmering situation as in figure 8.31. Efficient insulation reduces temperature fluctuations with a possibility to maintain high temperature peak for

as long as required. Operating the technology over many hours (4.5 or 4.16) indicates that oven temperature variation result from loading which causes cooling.

High gas production leads to flame increase and higher temperature which accelerates the entire system. To control excessive temperature rise, loading of plastics is reduced while water for steam is increased to cool system. The cooling gradient is very gradual indicating that system can be heated once and used over long time with gradual heat losses (Fig. 8.31).

### 8.5.7 Optimising Energy Generation and Utilization

Energy production and utilization depends on the demand, technology available and value of energy produced. High valued heat is applicable in cooking and heating for domestic applications. It was observed that when average temperature of the oven is 863°C, the oven top was 222.67°C, flame was 686.33°C and exhaust gas was 625°C. Much heat was observed to be lost through exhaust gases as proven by the excess heat accumulated around the chimney-casing inlet (Fig. 8.32). This was controlled by use of a heat exchanger and water heater to recover heat from exhaust gases.

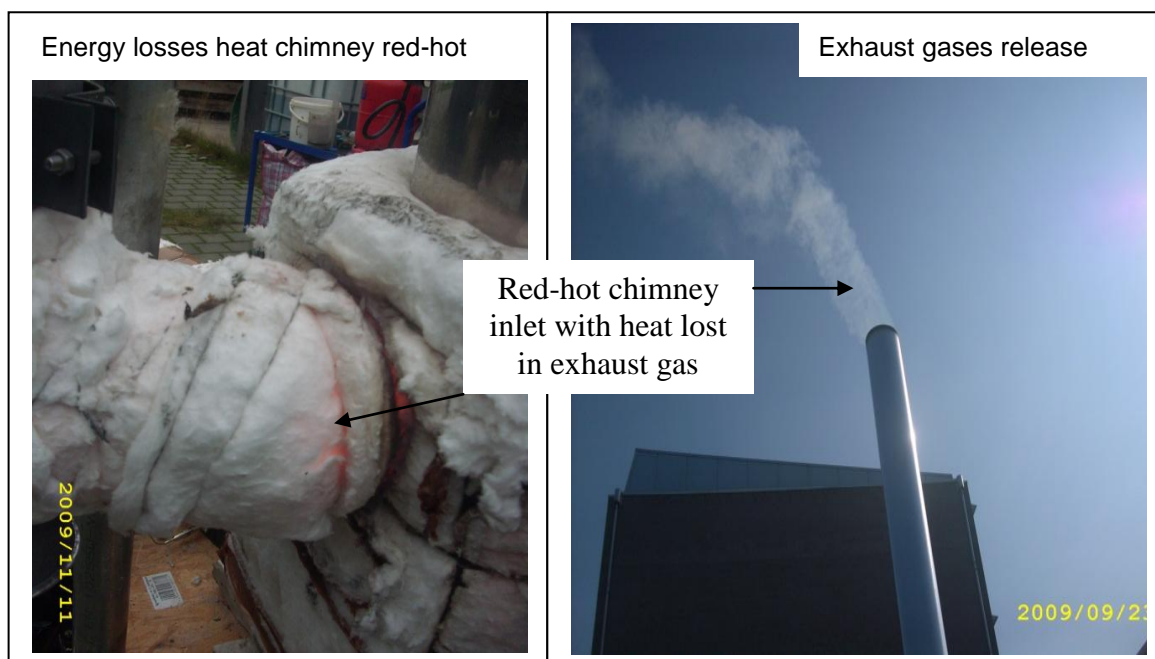


Figure 8.32 Heat losses through chimney and exhaust gases

In most tropical countries post-harvest crop processing and value addition systems involve drying, smoking and grilling using mainly heat. The lower value heat from using PG technology in combined heat power production or domestic cooking can be used for drying agricultural products e.g. cocoa, coffee, maize, groundnuts etc. Energy use



efficiency can be enhanced by integrating solar hot water systems and PG technology within a decreasing temperature dryer system.

### 8.5.8 Integration of Heat Exchanger and Water Heater

Running the system without a heat exchanger and water heating reservoir led to high heat losses. The average temperature values (°C) in one exercise were 863 inside the oven, 222.67 at top of the oven, 686.33 of flame and 625 for exhaust gases.

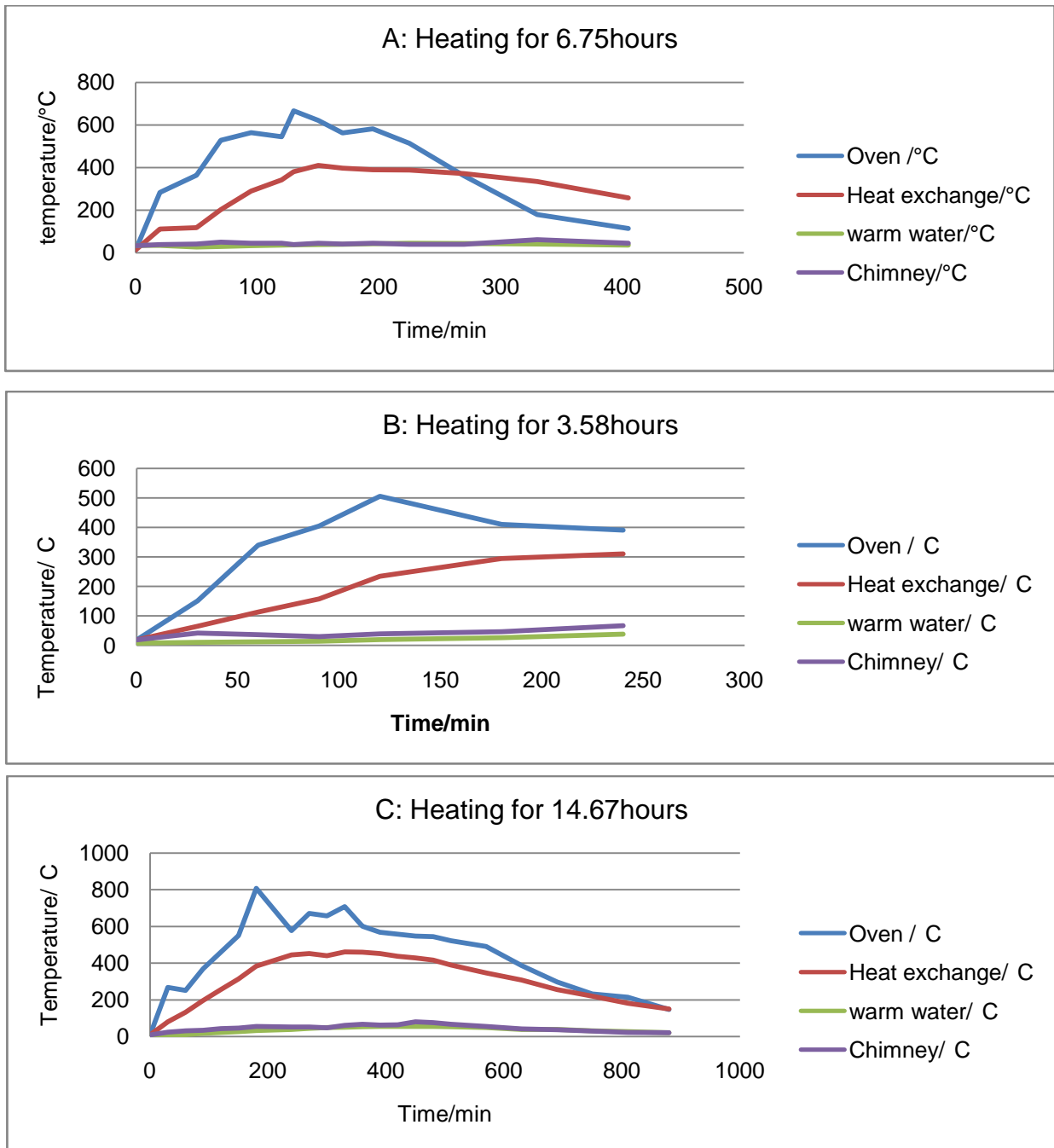


Figure 8.33 Temperature variations of oven, heat exchanger, water and chimney

Introducing the heat exchanger and water heater improved heat recovery (Fig. 8.33) as follows:

- Chimney and water temperature is consistent and low (18-80°C) but gradually rises during heating and drops during cooling
- The heat exchanger has the potential to store energy and release gradually on cooling
- Heat produced can be used as high (200-800°C), medium (90-200°C) and low (45-90°C) value to achieve 80-95% energy-use efficiency
- Integrating a heat exchanger and warm water heater improved energy recovery, oven temperature stabilization and reduced natural draft of exhaust gases.

#### **8.5.9 Comparing Water and PG Chamber Temperature Variations**

Insulation using glass wool was found to be less resistant to higher. Hence, Alsitra wool was used due to its better insulation and high temperature resistance. However, to minimize heat losses due to the high porosity, multiple layers of the Alsitra wool were used. Oven temperature fluctuations more when it was not insulated while water for boiling had steady temperature rise. The oven temperature was observed to fluctuate significantly compared to the water temperature.

To conclude, oven temperature fluctuation can be minimized using effective insulation but may not be eliminated when the system operates in open-air. Operating in an insulated compartment in which air is pre-heated as it flows in counter direct to hot exhaust gases will minimize temperature fluxes.

## Chapter Nine

### Material Balance Calculations in PG Technology System

#### 9.0 Heat and Mass Balance Analogies

Cost-effective energy recovery from high calorific waste requires a mass and energy balance analysis. Matter is transformed to energy when C-C and C-H chains break on heating at high temperature forming various inflammable monomers, active molecular groups and other smaller molecules which are burned.

Table 9.1 An analogy of heat and mass transfer

|  |                                      | Heat transfer   | Mass transfer   |
|--|--------------------------------------|---|---|
| Nature                                 |                                      | Transfer of thermal energy within a single phase  | Transfer of chemical components from a donor to host phase within a phase                             |
| Mechanisms                             | Molecular movement in closed systems | Heat conduction in metal and transfer of hot gas stream   | Diffusion and transfer of hot gases involving phase changes   |
|  | Macroscopic movement (gases)         | Convective and conductive heat transfer   | Convective mass transfer (molecules)  |
|  | Radiation                            | Thermal radiation   | No mass radiation   |
| Technical meaning                      |                                      | Favouring heat transfer (temperature gradient)<br>Prevention of heat transfer by insulation and isolation | Cracking of polymer plastics, transfer of pyrolysis-synthesis gases to combustion chamber and burning |
| Transport equation                     |                                      | Heat and material flow rates and driving forces (temperature, concentration and pressure)                 |   |
| Transport area                         |                                      | Heat transfer surface   | Mass of hot gases   |
| Driving forces and intensive variables |                                      | Temperature difference  | Concentration, composition, phase change and pressure differences                                     |
| Examples                               |                                      | Heat conduction, radiation and convection (free and forced)   | Drying and dissolving of solids, absorption of gases and distillation                                 |

The PG technology involves a dynamic mass and heat transfer system ensuring effective resource recovery from waste. An analogy of heat and mass transfer is summarized in table 9.1. To estimate the cost-effectiveness and affordability of the PG technology to developing countries requires mass and energy balances. A careful evaluation of the energy and mass balance analysis of the simplified process is absolutely necessary to ascertain the environmental friendliness of the technology.

## 9.1 Energy and Mass Input and Output in PG Process

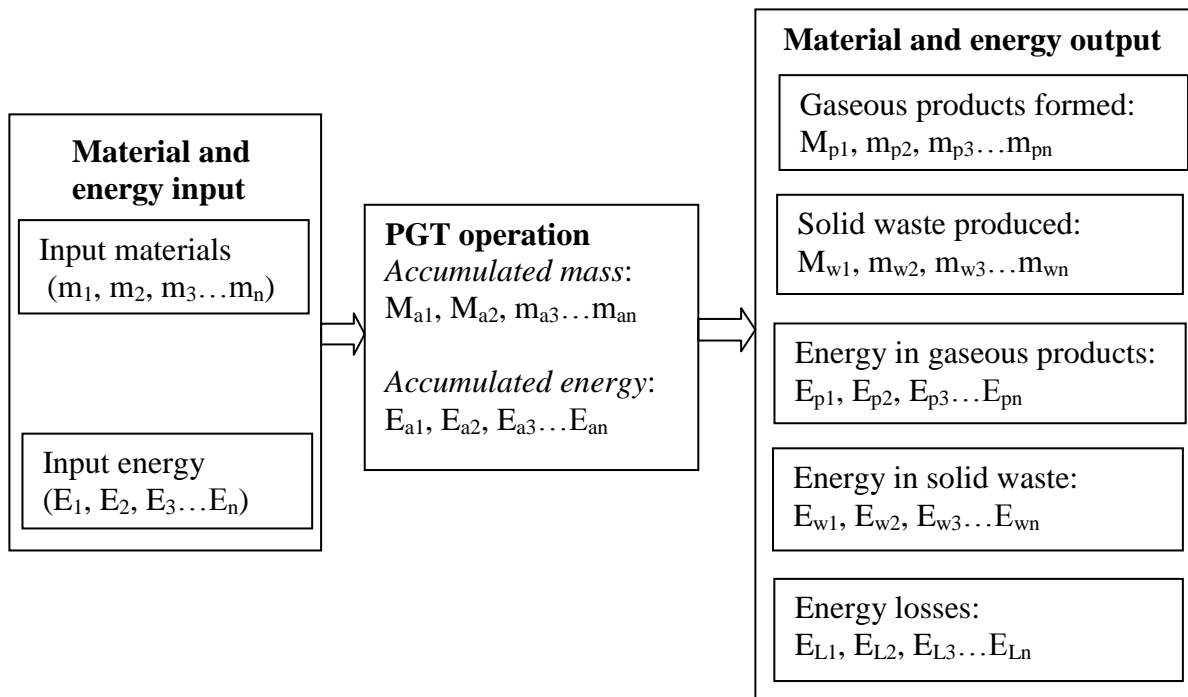


Figure 9.1 Modelling the energy and mass calculations

The PG technology functions as an open system governed by the law of conservation of matter and energy. Hence, various material and energy inputs undergo conversions that lead to accumulations and output. The mass and energy analysis mainly involve the transformation of mass (plastics waste and charcoal) through cracking and burning liberating various energy forms, exhaust gases and residue ash (Fig. 9.1).

## 9.2 Mass Balance within the PG Process

The law conservation of mass or energy states that in every chemical and physical process, matter can neither be created nor destroyed but can be transformed from one form (mass or energy) to another (Eq. 9.1).

$$\sum Q + \sum W = 0 \dots\dots\dots 9.1$$

Applying the non-flow conservation of energy law to the PG process involves an integrated of physical and chemical changes sustained by net heat transformation (Q) involving internal energy (U) and work (W) changes (Eq. 9.2).

$$U_2 - U_1 = \sum_1^2 dQ + \sum_1^2 dW \dots\dots\dots 9.2$$

Applying the law of conservation of mass using [ $M_i$  (mass in),  $M_o$  (mass out),  $M_g$  (mass generated) and  $M_a$  (mass accumulated)] gives equation 9.3.

$$M_i - M_o + M_g = M_a \dots\dots\dots 9.3$$

The application of this principle is necessary for quantifying solid and gaseous waste released for pollution prevention auditing. This follows a systematic procedure for identifying ways to reduce or eliminate material and energy wastage (Fig. 9.2).

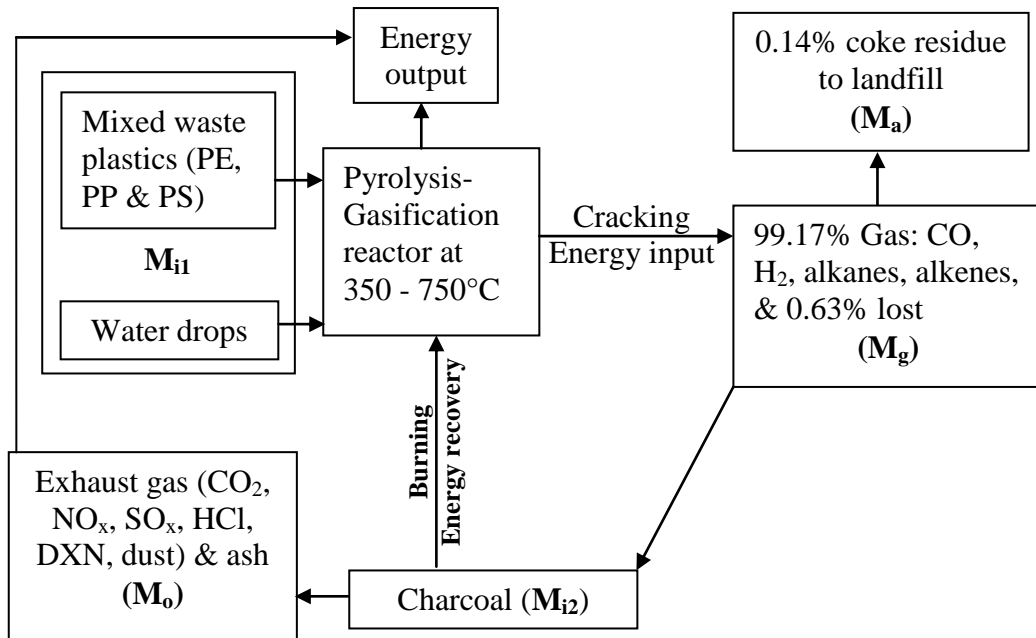


Figure 9.2 Simplified mass and energy balance model

This requires a quantification of fugitive emissions including evaporative losses. This helps in tracking the flow and characterisation of the waste. This involves the measuring and evaluation of the performance of the implemented pollution prevention options (Fig. 9.2). The application of pollution prevention strategies offers a cost-effective method of eliminating or minimising waste generation in the production process. Although various plastics have different activation energy values, they typically decompose randomly on thermal cracking yielding mainly alkanes, alkenes, hydrogen, carbon monoxide and other high-boiling-point hydrocarbon products.

## 9.2.1 Comparison of Component Yields for Thermal and Catalytic Cracking

Table 9.2 Comparison of thermal and catalytic cracking

|                    | Property                      | HDPE   | LDPE           | LP           | PP                         | PS     | Average |
|--------------------|-------------------------------|--|----------------|--------------|----------------------------|--------|---------|
| Thermal cracking   | Liquid yield (%)              | 91.30  | 91.71          | 93.80        | 91.05                      | 99.02  | 93.38   |
|                    | State of liquid               | Milk white   | Milk white     | Milk white   | Yellow                     | Rufous |         |
|                    | Product at normal temperature | Wax  | Wax            | Wax          | Solid & liquid mixture     | Liquid |         |
|                    | Gas yield (wt %)              | 7.61   | 7.42           | 5.60         | 7.60                       | -      | 7.06    |
|                    | Coke yield (%)                | 0.14   | 0.15           | 0.14         | 0.14                       | 0.15   | 0.14    |
|                    | Total yield (%)               | 99.05  | 99.28          | 99.54        | 98.79                      | 99.17  | 99.17   |
|                    | Lost (%)                      | 0.95   | 0.72           | 0.46         | 0.21                       | 0.83   | 0.63    |
| Catalytic cracking | Liquid yield (%)              | 76.81  | 77.40          | 85.20        | 87.20                      | 86.20  | 82.57   |
|                    | State of liquid               | Solid +  | Solid +        | Light yellow | Light yellow               | Rufous |         |
|                    | Product at normal temperature | Liquid mixture   | Liquid mixture | Liquid       | Liquid                     | Liquid |         |
|                    | Gas yield (wt %)              | 14.08  | 14.08          | 8.15         | 9.34                       | 0.34   | 9.20    |
|                    | Coke yield (%)                | 8.04   | 8.04           | 6.52         | 3.35                       | 13.02  | 7.80    |
|                    | Total yield (%)               | 99.79  | 99.79          | 99.87        | 99.89                      | 99.56  | 99.78   |
|                    | Lost (%)                      | 0.21   | 0.21           | 0.13         | 0.11                       | 0.44   | 0.22    |
| General properties | Temperature range (°C)        | 400-450  | 420-450        | 450-650      | 450-640                    |        |         |
|                    | Conversion rate (%)           | 95% oil products   |                |              | 50-80% in catalyst & water |        |         |
|                    | Characteristic products       | Oil: C <sub>10</sub> -C <sub>30</sub> (94.5%); Gas: H <sub>2</sub> , C <sub>1</sub> -C <sub>5</sub> (5.5%); Olefins (65%); Terminal olefin (35%); Non terminal olefin (5%) |                |              | Qualified gasoline for use |        |         |

Source: Adapted from Yaun, 2006

However, the yield of a light fraction composed of mainly ethylene, propylene and methane keeps growing with increase temperature. Heating a mixture of waste plastics (excluding PVC) to between 300-550°C and water vapour added to obtain a gasification product gives a mixture of very inflammable gases containing mainly H<sub>2</sub>, CO, CO<sub>2</sub> and CH<sub>4</sub>. Table 9.2 presents a mass balance based on percentage yields of component products from thermal and catalytic cracking of major polyolefins.

The table confirms the improvements cause by catalyst action compared to thermal cracking but results in 7.8% against 0.14% of coke yield respectively. The carbon deposited in the PG chamber results from pyrolytic carbon and inert components of the feedstock (Furusa et al., 1998). Considering the extra cost of catalyst and its chamber installations as well as catalyst treatment, thermal cracking is favourable.

### 9.2.2 Modelling the Mass Balance System

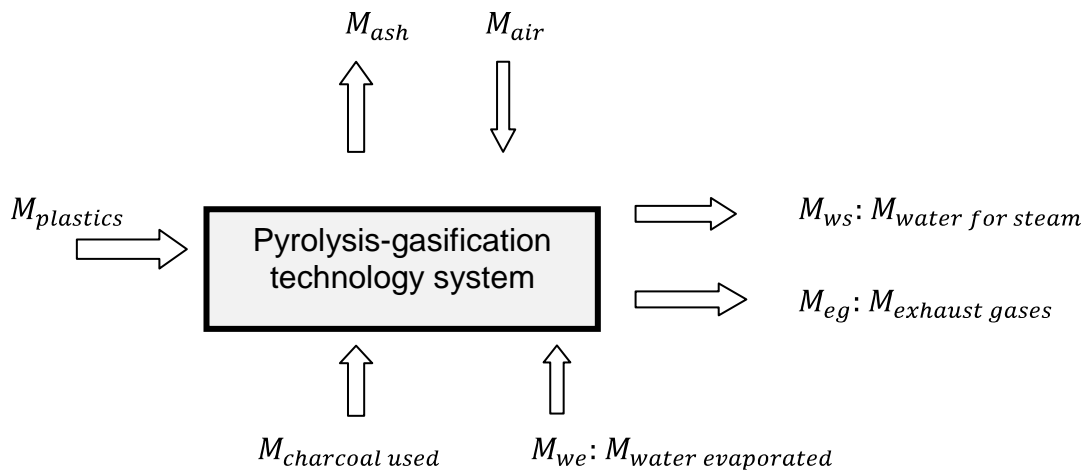


Figure 9.3 Modelling the mass balance system

The mass balance analysis focuses on input, converted, output and stored materials in mainly solid and gaseous states (Fig. 9.3). The PG system involves batch and continuous processes with masses of important components calculated in kilograms. Some quantities have been grouped to simplify calculations but without compromising quality and efficiency of results given the complexity of the systems.

Multiple processes including heating, drying, melting, evaporating and cracking involving various chemical and physical reactions occur. This leads to various products components which are further burned producing an exhaust gas. Hence, equation 9.4 presents a mass balance in the PG system. It considers pure PE (non-PVC plastics) converted into mainly CO, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub> and other C<sub>2</sub>-C<sub>4</sub> hydrocarbon molecules which are burned completely to recover energy with exhaust gases produced (mainly of CO<sub>2</sub> and H<sub>2</sub>O).

$$M_{air} + M_{ash} + M_{eg} + M_{we} = M_{plastic} + M_{ws} + M_{charcoal} \dots \dots \dots 9.4$$

In applying equation 9.4, the following assumptions are considered:

1. The mass balances involve only energy producing components (plastics and charcoal)
2. Water input as steam is released as steam with energy input being equal to output i.e. M<sub>we</sub> and M<sub>ws</sub> could be eliminated from equation 9.4 to obtain 9.5.

$$M_{air} + M_{ash} + M_{eg} = M_{plastic} + M_{charcoal} \dots \dots \dots 9.5$$

Determining the masses of air and exhaust gases given the intervention of O<sub>2</sub>, H<sub>2</sub>, CO<sub>2</sub> and steam from the air and PG system becomes very complex. Considering that only O<sub>2</sub> is used from air which combines with combustion products to exhaust gases which are all non-energy producing components,  $M_{air}$  could be eliminated from equation 9.3 to get equation 9.6.

$$M_{ash} + M_{eg} = M_{plastics} + M_{charcoal} \dots \dots \dots 9.6$$

Hence, mass of exhaust gases is given by equation 9.7:

$$M_{eg} = M_{plastics} + M_{charcoal} - M_{ash} \dots \dots \dots 9.7$$

Table 9.3 summarizes the mass balance approach of the charcoal and plastic waste used in various experiments. Adapting the results of the pyrolysis-gasification of HDPE plastic in steam and sand conducted by Wu and Williams (2010), it can be concluded that 97.60% (0.5368kg) of PE was effectively transformed into CO (26%), H<sub>2</sub> (39%), CH<sub>4</sub> (14%), C<sub>2</sub>-C<sub>4</sub> (20%) and CO<sub>2</sub> (1%). All the gases except CO<sub>2</sub> combine with O<sub>2</sub> in the combustion chamber to produce CO<sub>2</sub> and H<sub>2</sub>O (steam).

Table 9.3 Material balance in PG process

| Material   | Mass (kg)   | %   | Energy released (MJ/kg)         |
|--|-------------|---|---------------------------------|
| Charcoal input                                   | 1.65        | 100.00                                      |                                 |
| <b>Charcoal used (<math>M_{charcoal}</math>)</b> | <b>1.40</b> | <b>84.85</b>                                | <b>26.88 (heat &amp; light)</b> |
| Ash produced ( $M_{ash}$ )                       | 0.25        | 15.15                                       |                                 |
| Plastic input (PE) [ $M_{plastics}$ ]            | 0.55        | 100.00                                      |                                 |
| <b>Plastic used (PE)</b>                         | <b>0.54</b> | <b>97.60</b>                                | <b>24.69 (heat &amp; light)</b> |
| Char from plastic (carbon)                       | 0.0132      | 2.40  | (burned)                        |
| Mass of exhaust gases                            | 1.70        | Mainly CO <sub>2</sub> and H <sub>2</sub> O |                                 |

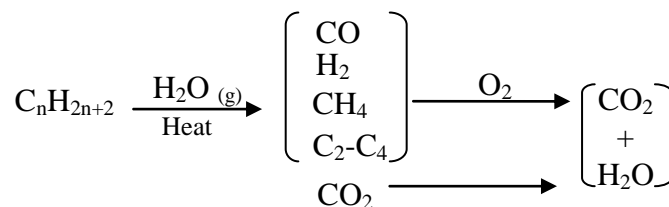


Figure 9.4 Schematic representation of the pyrolysis-gasification of PE

The material balance analysis has been summarized due to the absence of relevant technological equipment to carry out a more detailed assessment of the masses of



components of the C<sub>2</sub>-C<sub>4</sub> hydrocarbons that reach the combustion chamber. Determination of such information facilitates the calculation of CO<sub>2</sub> produced and/or gained by energy recovery from high calorific value waste. This is essential for the assessment of carbon credits (Fig. 9.4).

### **9.2.3 Impact of Temperature and Residence Time on Gaseous Products**

Pyrolysis of HDPE pellets yields liquids and gases with significant variations in quantity between 500-700°C due to changes in the reaction rate. Composition and quality of the gaseous products depend on the residence time of the primary pyrolysis products in the hot reaction zone. This indicates the relevance of secondary and tertiary reactions to pyrolysis-synthesis gas formation (Ludlaw-Palafox and Chase, 2001). This proves the importance of the relationship between temperature and residence time with respect to the sensitivity of pyrolysis reactions. Applying pyrolysis in treating laminated plastics offered some advantages, understanding and explanations:

- Main products from the degradation of plastics included linear hydrocarbons, alkenes, alkanes, dialkenes making about 81-93% and 7-19% made up of wax/oils composed of very complex mixture of cyclic and branched aliphatic and aromatic compounds
- The process was used in the treatment of Aluminium-polymer laminates with 100% recovery of polymer with clean shiny surfaced aluminium.
- X-ray florescence spectrometry analysis of plastics waste (gaseous, liquid and solid fuels) shows that the elements detected in the higher amount was titanium while lead, sulphur, calcium, silicon, aluminium, magnesium, zinc, chlorine, sodium, potassium were detected in very low amounts (Costa et al., 2007)

Hence, PG reaction is first order forming an irreversible thermal cracking of plastics which serves as an excellent method of separating laminated Aluminium-plastics.

### **9.2.4 Application of the Mass Balance Analysis**

A series of experiments were conducted using the optimized PG technology with relevant data was collected. In an experiment carried out at surrounding temperature of 24°C in moderate windy conditions. 1.65kg of charcoal was used with 1.5327kg burned releasing 0.0498kg of ash and unburned charcoal of 0.1173kg. In addition, 0.3266kg of plastics was transformed to pyrolysis-synthesis gas and burned in-situ producing 0.0046kg of residue carbon.

A pot of mass 0.9kg containing 3.05Kg of water initially weighed 3.95kg and after heating to boil, simmering and cooling for 235 minutes (3.91hours), weighed 3.10kg indicating that 0.85kg of water was evaporated. The heating of water raised the temperature from 28°C to 100°C (120minutes), simmering (50minutes) and cooling to 78°C for 65minutes. 0.0813kg of water was used for steam generation in the PG chamber. Applying the mass balance equations 9.1 to 9.7 in experiments (E2006, E2206 and E2101) the values in table 9.3 were generated.

Table 9.4 Summary of mass balances for optimised PG technology experiments

| Quantity calculated/kg   | Value/unit |       |        |       |        |       | Av. /kg | Av. %        | Remark                                       |
|--|------------|-------|--------|-------|--------|-------|---------|--------------|--|
|  | E2006      | %     | E2206  | %     | E2101  | %     |         |              |  |
| Charcoal used  | 1.5327     | 89.1  | 1.68   | 98.21 | 1.85   | 82.7  | 1.69    | <b>89.25</b> | <i>Equations 9.1 – 9.7 have been applied</i> |
| Ash produced   | 0.0498     | 3.25  | 0.01   | 0.60  | 0.02   | 1.08  | 0.03    | <b>1.87</b>  |  |
| Rest of charcoal   | 0.1173     | 7.65  | 0.02   | 1.19  | 0.3    | 16.22 | 0.15    | <b>8.88</b>  |  |
| Plastic used   | 0.3266     | 99.27 | 0.50   | 98.14 | 0.6    | 96.72 | 0.48    | <b>97.21</b> |  |
| Plastic-C. residue   | 0.0046     | 1.41  | 0.0079 | 1.58  | 0.0132 | 2.2   | 0.01    | <b>2.08</b>  |  |
| Plastic-C ash  | 0.0024     | 0.73  | 0.0014 | 0.28  | 0.0065 | 1.08  | 0.0034  | <b>0.71</b>  |  |
| Water for steam  | 0.0813     | -     | 0.1086 | -     | 0.1525 |       | 0.1141  | -            |  |
| Water in pot evaporated  | 0.85       | -     | 0.7    | -     | 0.7    |       | 0.75    | -            |  |
| Total average input mass: 1.69kg + 0.48kg – 0.15kg   |            |       |        |       |        |       | 2.02    | <b>98.51</b> |  |
| Total average output mass: 0.03kg + 0.0034kg   |            |       |        |       |        |       | 0.03    | 1.49         |  |
| NB: Average % indicates effective weight% of materials transformed into energy (heat & light). |            |       |        |       |        |       |         |              |  |

Observations on data obtained from mass balance calculations (Table 9.4):

1. Averagely 89.25% of the charcoal introduced into the combustion chamber is burned releasing 1.87% of ash with 8.88% unburned charcoal for each batch from heating, simmering and cooling.
2. Averagely 97.21% of waste plastics introduced into the PG chamber are transformed into pyrolysis-synthesis gas with 2.08% of plastic carbon residue which when burned in combustion chamber gives about 0.71% of ash.
3. Evaluating the overall mass balance, 98.51% of charcoal and plastics introduced into the PG technology releases 1.49% of waste (mainly ash) which can be disposed in landfills or used as soil supplements.

- Consequently, 99.29% of landfill space is saved with respect to plastic disposal as over 99% of the energy in plastic waste is released essentially as heat for various applications

### 9.3 Energy Balance Calculations in PG Technology System

Developing a technology for producing energy in an environmentally friendly manner is the main goal of this research. Hence energy balance has been treated as a core issue. Although the various energy types and conversion occur at different stages with multiple impacts on the temperature-driven system, effort has been made to significantly simplify the thermal inter-conversion.

#### 9.3.1 Pyrolysis of Waste Plastics into Liquid Fuels

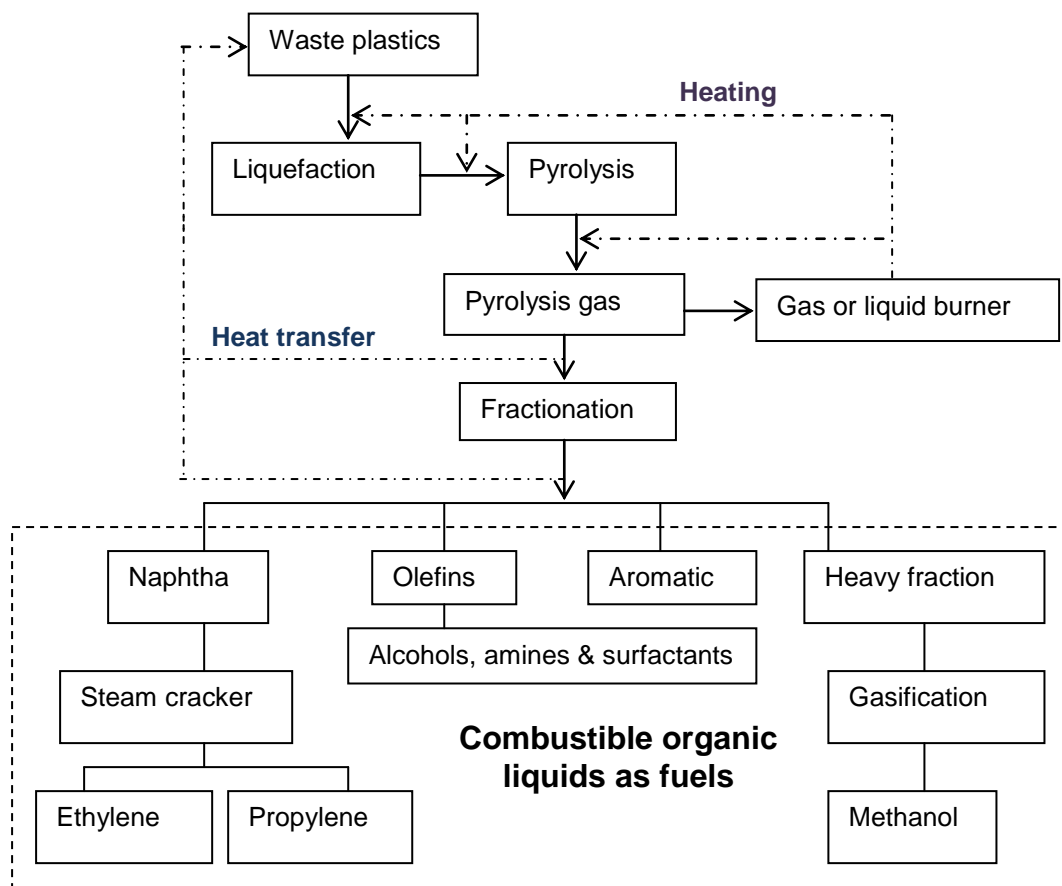


Figure 9.5 Current application of pyrolysis in plastic waste management

Since the 1970s, shortage in energy and desire to control environmental pollution has become a more serious global concern. This has motivated various researches in which plastic polymers are cracked to obtain liquids that are then fractionally distilled to obtain

fuels. Figure 9.5 presents the schematic flow of energy (dotted lines) and materials (hard lines) in current state-of-the-art technologies used to convert waste plastics to fuels.

### 9.3.2 Applicable Energy Fundamental Principles

Table 9.5 Valuable thermodynamic concepts

|                              |   |   |
|------------------------------|---|---|
| Thermodynamic concept        | Facts with relevant symbolic representation   |   |
| Heat (Q)                     | <ul style="list-style-type: none"> <li>- Energy transferable by virtue of temperature difference to attend thermal equilibrium</li> <li>- Exothermic (heat released) and endothermic (heat absorbed) processes</li> </ul>   |   |
| Work (W)                     | Force multiplied by the distance in the direction of the force  |   |
| Temperature (T)              | Temperature is measured of the heat content of a body and the PG process is scaled independent of the working substance   |   |
| Pressure (p)                 | Force per unit area of system boundaries  |   |
| System                       | Open  | Collection of matter and energy within prescribed and identified boundaries <i>with</i> transfer across boundaries    |
|                              | Closed  | Collection of matter and energy within prescribed and identified boundaries <i>without</i> transfer across boundaries |
| Conservation of energy law   | Energy can neither be created nor destroyed but can be transformed into other forms   |   |
| First law of thermodynamics  | The intrinsic energy change of a system undergoing a thermodynamic cycle with net heat supplied to and net work input from system's surroundings is zero<br>( $\sum Q + \sum W = 0$ )   |   |
| Second law of thermodynamics | <p>In any complete cycle the gross heat supplied plus the net work input must be greater than zero ( <math>Q &gt; -W</math> ) or</p> <p>It is impossible to construct a device which operating in a cycle produces no other effect other than the transfer of heat from a cooler to a hotter body ( <math>w &gt; 0</math> ). This implies that cycle efficiency (<math>\eta</math>) is always less than unity (<math>\eta = -W/Q</math> )</p> |   |

The scientific study of the mutually convertible relationships between heat and mechanical work as energy forms with system properties is known as applied thermodynamics. The understanding of this inter-linkage between energy forms (heat and work) including their inter conversion within prescribed and identifiable system properties is governed by the first and second laws of thermodynamics (Table 9.5). Kinetic studies of pyrolysis of synthetic polymers in isothermic and dynamic regimen can help identify polymers with their activation energy (Encinar and González, 2008).

This shows the amount of energy required per mole of the specific polymers for thermal degradation which is relevant to determine how much energy is required to initiate the

pyrolysis process. In the PG technology the activation energy is initially acquired from burning charcoal and released on combustion of hot pyrolysis-synthesis gas mixture.

### 9.3.5 Basis of Energy Balances and Analysis

The estimation of energy quantities flowing through or involved in process operations are described as energy balances. Since materials burn to produce energy, both material and energy balances are governed by the conservation and thermodynamic laws. Attention is paid here on energy balances based on the following assumptions:

- Intervention of multiple energy transformation are group based on the location
- Bond breaking and formation produces and consumes energy which all released in the combustion chamber.
- Insulation reduces energy losses enhancing localization and grouping energy forms and the self-sustainability of systems
- Total system energy can neither be created nor destroyed. Hence, the temporary increase in stored energy is difference between incoming and outgoing flow of energy and energy produced.

In modelling the overall material and energy operation, a black box approach is applied where emphasis is laid on input and output results. The overall mass and energy balance with respect to raw materials used, the products formed, waste produced and stored products is summarised below. Hence mass of raw materials ( $M_I$ ) is equal to the sum of the mass of products ( $M_P$ ), mass of stored materials ( $M_S$ ) and mass of waste ( $M_W$ ) released [equations 9.6 and 9.7].

$$\text{Raw materials input} = \text{Products} + \text{Wastes} + \text{Stored materials} \dots \dots \dots 9.6$$

$$\sum_{n=1}^n m_I = \sum_{n=1}^n m_w + \sum_{n=1}^n m_p \dots \dots \dots 9.7$$

Energy input ( $E_I$ ) equals energy output in products ( $E_P$ ), waste ( $E_W$ ), heating ( $E_H$ ) and absorbed ( $E_a$ ) [equation 9.8 & 9.9].

$$\text{Energy input} = \text{Energy output} - \text{Energy stored} \dots \dots \dots 9.8$$

Energy stored ( $E_s$ ) becomes zero when systems cools to original temperature (making  $E_s = 0$ ). Hence, energy input ( $E_I$ ) is equal to energy output ( $E_o$ ):

$$\sum_{n=1}^n E_i = \sum_{n=1}^n E_0 = \sum_{n=1}^n E_p + \sum_{n=1}^n E_w + \sum_{n=1}^n E_h + \sum_{n=1}^n E_a \dots \dots \dots 9.9$$

### 9.4 Modelling the Energy Balance System of the PG Technology

Various energy transformations occur with the PG system considered as a 'black box' with input energies (arrows pointing inwards), output energies (arrows pointing outwards) and internal energy exchanges or recycling (double arrows) (Fig. 9.6). The variable energy quantities and energy transfer interactions make the modelling of the energy balances much more complex. Hence some assumptions have been taken to simplify the calculations.

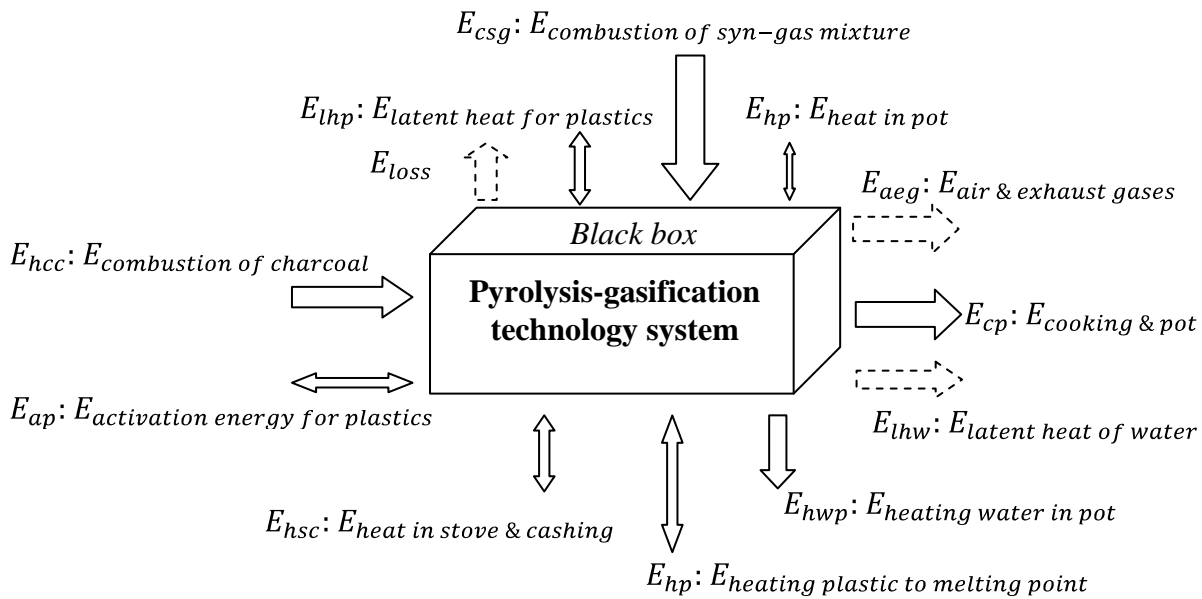


Figure 9.6 Modelling the detailed energy system of the PG technology

#### 9.4.1 Energy System Simplification

The energy balance equation eliminates energy components linked by a double arrow since these components are gained and released within the system based on the black box assumption. Figure 9.7 indicates the energy component groups resulting from the internal energy dynamics within the energy system transformations. This simplifies the energy balance calculations with little influence on energy production and performance efficiency. The energy exchanges occur mainly in the PG technology system, the water in pot system and the surroundings.

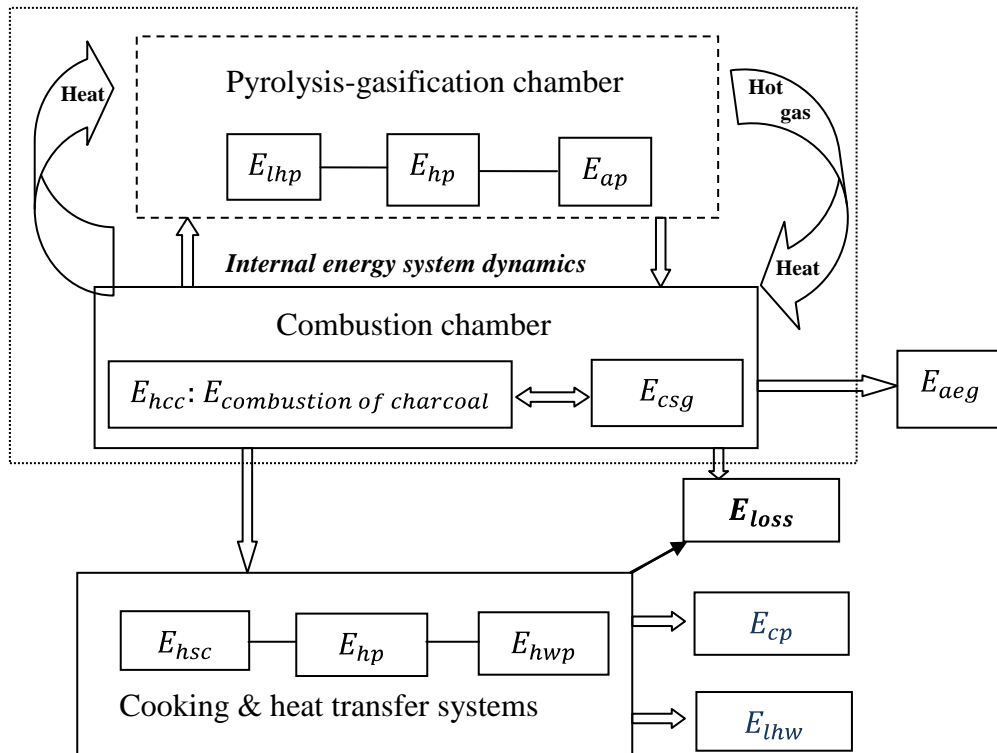


Figure 9.7 Modelling the simplified energy balance system

### 9.4.2 Simplified Energy Balance Equation

Emphasis is here laid on establishing a balance between the main energy production, consumption and loss processes. However, the latent heat of vaporisation for water is of relevance to boiling, simmering or cooking which are linked to heat used to heat. With efficient insulation, the energy transfer and performance efficiency is a function of the total energy produced and total energy used in performing a specified task.

$$E_{\text{generation}} = E_{\text{csg}} + E_{\text{hcc}} = E_{\text{loss}} + E_{\text{ha}} + E_{\text{lhw}} + E_{\text{hwp}} + E_{\text{cp}} \dots\dots\dots 9.10$$

### 9.4.3 Energy Use Efficiency in the PG Technology

The energy use efficiency is a percentage of energy effectively used for a designated purpose. Equation 9.11 gives the energy efficiency for the PG technology which is the percentage of energy effectively used compared to energy input.

$$\text{Energy use efficiency} = \frac{E_{\text{lhw}} + E_{\text{hwp}} + E_{\text{cp}}}{E_{\text{csg}} + E_{\text{hcc}}} \times 100 \dots\dots\dots 9.11$$

### 9.4.4 Energy Recovery from Plastic Waste

Energy used efficiency is a fraction of the total energy produced by the system since energy losses can never be zero. With effective insulation energy losses can be

reduced to minimum. The total energy input (Eq. 9.12) can approximate that used by enhancing the energy recovery system.

$$E_{\text{plastics}} = E_{\text{loss}} + E_{\text{ha}} + E_{\text{lhwh}} + E_{\text{hwhp}} + E_{\text{cp}} - E_{\text{hcc}} \dots\dots\dots 9.12$$

Percentage of energy produced by plastic is a fraction of the total input energy (Eq. 9.13). This depends on the plastic feeding rate and consistency as well as the calorific value of the plastic type used.

$$\text{Percentage of energy from plastics} = \frac{E_{\text{plastics}}}{E_{\text{csg}} + E_{\text{hcc}}} \times 100\% \dots\dots\dots 9.13$$

**9.4.5 Effective Useful Energy**

Percentage of energy used for intended purpose compared to total energy input gives the energy efficiency of the PG technology (Eq. 9.14). Improving energy efficiency is achievable through the application of multiple temperature recovery systems involving high to low value heat.

$$\text{Percentage of usable energy or energy efficiency} = \frac{E_{\text{lhwh}} + E_{\text{hwhp}} + E_{\text{cp}}}{E_{\text{csg}} + E_{\text{hcc}}} \times 100 \dots\dots\dots 9.14$$

**9.4.6 Calculation of Heat Lost Through Air and Exhaust Gases**

In determining the heat lost through air and exhaust gases, certain measurable variables are considered. Equations 9.15, is applied in determining the air velocity and air flow volume which are dependent on the temperature differences, where:  $v_e$  is airflow velocity (m/s);  $g$  is acceleration of gravity ( $m/s^2$ ): 9.81;  $l$  is vertical distance from primary air entrance to top of stark (m);  $dt = t_e - t_s$  is temperature difference between surroundings and stark outlet;  $t_s$  is exhaust gas outlet temperature ( $^{\circ}C$ );  $t_e$  is temperature of surrounding environment ( $^{\circ}C$ );  $Q$  is air flow volume ( $m^3/s$  per meter surface width);  $L$  is latent heat of vaporization for water;  $M_w$  is mass of water;  $M_p$  is mass of plastics; and  $M_c$  is mass of charcoal

$$w = \frac{\dot{Q}}{\rho A C_c \Delta T} \dots\dots\dots 9.15$$

The air velocity ( $V_e$ ) which depends on the temperature changes and distance between air inlet and exhaust gas outlet is calculated using equation 9.16.

$$V_e = 0.65 [g(t_s + t_e)/273 + t_e]^{1/2} \dots\dots\dots 9.16$$



**Convective air flow volume (Q):**

Any heat source will generate a convective vertical air flow with quantity of air flow estimated using equation 9.17. Quantity of air flow rate ( $\dot{Q}$ ) is given by equation 9.18.

$$Q = 0.019 [g(t_s - t_e)/(273 + t_e)]^{0.4} I^{1.2} \dots\dots\dots 9.17$$

Quantity of air flowing rate ( $\dot{Q}$ ) through the oven depends on the air density, velocity and outlet area is calculated using equation 9.18.

$$\dot{Q} = \rho v A \dots\dots\dots 9.18$$

During the functioning of the PG technology, air flow, flow direction and degree of turbulence is very essential for the following reasons:

- Turbulence at the beginning of the process is higher which reduces over time leading to almost laminar flow
- During laminar flow, only the consumption of oxygen during burning causes air in-flow which corresponds to exhaust gas out-flows

Inlet air flow is unlimited ensuring excess oxygen supply where  $n > 1$  for over stoichiometric operations. This ensures complete combustion and safe operation. However, this tends to lower temperature resulting in high operation cost. The stoichiometric equation is given by:

$$n = \frac{\text{Oxygen supplied to combustion process}}{\text{Minimum oxygen demand for complete fuel oxidation}} \dots\dots\dots 9.19$$

Values of n lie in the range  $1 \leq n \leq 1$  where under stoichiometric ( $n < 1$ ) and stoichiometric ( $n = 1$ ) conditions occur but are not favourable due to high potential of incomplete combustion during thermal decomposition of fuels.

**9.5 Energy Required for Phase Changes and Heating**

The amount of energy (Q) required for phase change occurs at constant temperature when waste plastic is converted to liquid or gas during cracking (Eq. 9.20). Various phase changes occur at different stages resulting in latent heats of fusion and vaporization. This energy for phase transformation is collected from the charcoal and released in the combustion chamber during the burning of the pyrolysis-synthesis gas mixture.

$$Q_{\text{phase change}} = mL \dots \dots \dots 9.20$$

Quantity of energy required for heating with temperature changes of the technology system and water are calculated using equation 9.21.

$$Q_{\text{temperature change}} = mc\Delta T \dots \dots \dots 9.21$$

Total energy change ( $\Delta Q_{\text{total}}$ ) is the sum of energy consumed during the phase changes ( $\Delta Q_{\text{phase change}}$ ) and temperature of the substance ( $\Delta Q_{\text{temperature change}}$ ) presented by equation 9.22.

$$\Delta Q_{\text{total}} = \Delta Q_{\text{phase change}} + \Delta Q_{\text{temperature change}} = mL + mc\Delta T \dots \dots \dots 9.22$$

### 9.5.1 Conductive Heat Transfer

Conduction will take place if there exist a temperature gradient within a solid (or stationary fluid) medium. Energy is transferred from more energetic to less energetic molecules when neighbouring molecules collide. Conductive heat flow occurs in direction of the decreasing temperature since higher temperature is associated with higher molecular energy. Conductive heat transfer can be calculated using *Fourier's law* (Eq. 9.23).

$$q = \frac{kA\Delta T}{s} \dots \dots \dots 9.23$$

Where A is heat transfer area (m<sup>2</sup>); k is thermal conductivity of the material (W/m.K): 70 W/m<sup>o</sup>C; ΔT is temperature difference across the material (°C) and s is material thickness (m). Conductive heat transfer within the PG technology is influenced by system temperature including temperature changes. Effective insulation will reduce unwanted conductive heat transfer (heat losses) stabilizing the internal temperature of the system and enhancing heat use efficiency. Hence due to the insulation of the casing walls, conductive heat transfer is assumed to occur only at the top between pot-oven contact surfaces.

### 9.5.2 Applying Conductive Heat Transfer

The thermodynamic calculations of this process assumes steady state conditions since little significant mechanical or shaft work exchange occur between the system and surroundings (W is zero). The omission of continuous flow state conditions is an over estimation that should however be considered with caution. This is relevant since

feedstock loading and flow of pyrolysis-synthesis gas undergo continuous flow at constant volume though these effects are considered insignificant. Table 9.6 identifies the major energy forms and summarizes results of energy balance calculations.

The calculation of the various forms of energies involved can be done using the formula (mL). Heat used for phase change of water from liquid to vapour known as latent heat of vaporization ( $L_v$ ) is 2.257 MJ/kg. Characteristics of charcoal used in most of the experiments: bulk density 525.6kg/m, ash content 0.048%, moisture 8%, volatile matter 9%, carbon content 86% and calorific value 23.6MJ/kg [http://www.alibaba.com/product-free/106223469/hardwood\_Charcoal.html accessed 3.7.11].

Table 9.6 Summary of energy balance

| Item   | Value/unit    |              |               |              |               |              | Equations applied                      |
|--|---------------|--------------|---------------|--------------|---------------|--------------|--|
|  | E2006         |              | E2206         |              | E2101         |              |  |
| Quantity   | M (kg)        | H (MJ/kg)    | M (kg)        | H (MJ/kg)    | M (kg)        | H (MJ/kg)    | 9.8, 9.9, 9.10, 9.11, 9.12, 9.13, 9.20 |
| Charcoal used  | 1.5327        | 36.17        | 1.68          | 39.65        | 1.85          | 43.66        |  |
| Plastic used   | 0.3312        | 15.37        | 0.5079        | 23.57        | 0.6132        | 28.45        |  |
| <b>Total</b>   | <b>1.8639</b> | <b>51.54</b> | <b>2.1879</b> | <b>63.22</b> | <b>2.4632</b> | <b>72.11</b> |  |
| <b>% P:C ratio</b>   | <b>18:82</b>  | <b>30:70</b> | <b>23:77</b>  | <b>37:63</b> | <b>25:75</b>  | <b>40:60</b> |  |
| Water from pot evaporated  | 0.85          | 1.92         | 0.7           | 1.58         | 0.7           | 1.58         |  |
| <b>Heat unused</b>   |               | <b>49.62</b> |               | <b>61.64</b> |               | <b>70.53</b> |  |
| <b>NB:</b>   |               |              |               |              |               |              |  |
| <ul style="list-style-type: none"> <li>• <i>Unused heat include heat lost or stored and lost on cooling which otherwise can be used for heating, drying, baking and grilling as high and lower value heat</i></li> <li>• <i>Total mass [M (kg)] of charcoal (C) and plastic (P) used gives total energy</i></li> </ul> |               |              |               |              |               |              |  |

### 9.6 Reality in the Mass and Energy Balance Concept

Material and energy balances of the process are considered simultaneously. Hence, enthalpy is considered as the most important engineering function based on empirical evidence. It focuses on energy changes of the system compared to the amount of energy in a system. However, when the plastic material is transformed to energy, the decreasing rate of transformation to energy can be calculated using equation 9.24.

$$R_p = - \frac{\partial M_p}{\partial t} = - \frac{M_p}{t} \dots \dots \dots 9.24$$

Where  $R_p$  is decreasing rate of transformation of plastic to gas (negative sign) and  $dM_p$  is the change in mass of plastics during time period (t)

Reaction kinetics involving the study of reaction rates with intervening variable is considered critical in the analysis of reacting systems. In PG process emphasis is laid on variation in temperature and amounts of mass and energy per unit time.

### 9.6.1 Application of the Heat Produced in the Water Boiling Test

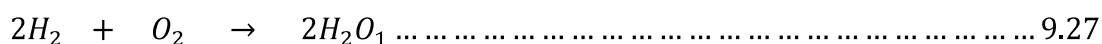
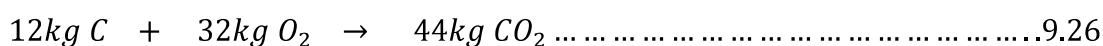
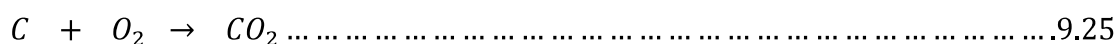
The PG technology targets the prevention of atmospheric and environmental pollution especially indoor air pollution (IAP) and to enhance energy use efficiency. The efficiency of channelling of the heat for use in heating and boiling water or other applications depends on the extent of avoidance of heat losses by effective insulation. Various laboratory based water boiling tests (WBT) were conducted to explore the most basic aspects of PG technology performance in controlled environment. These tests gave stable results with useful and quick feedbacks in laboratory settings. Effect of changes in technological design, fuel quality and other physical variables were evaluated.

### 9.6.2 Flexibility of the PG Technology to Various Fuel Types

The Technology is flexible to various solid fuel types providing opportunity to adapt the technology to various uses and multiple combustible waste fractions. In most developing countries with agric-driven economies, various types of organic waste are generated. These common waste forms with varied calorific values as measured under diverse conditions and circumstances can be used in PG technology. These substances could be used as co-fuels or initial heat providers.

## 9.7 Chemistry of the Combustion System

Charcoal and VOCs from plastics (fuels) combine with oxygen under stoichiometric conditions in weak air-fuel mixtures to give carbon dioxide and water.



PE has a carbon/hydrogen ratio of 1:2 respectively. Under stoichiometric conditions, all the carbon and hydrogen are converted to carbon dioxide and water respectively. Based on equations (9.25 to 9.28), mass in kilogram of CO<sub>2</sub> and steam produced including oxygen and air required can be calculated (Table 9.7).

$$CO_2 \text{ from carbon} = kM_c \dots\dots\dots 9.29$$

Table 9.7 Summary of input and output components

|   | Value/unit for experiments E2006, E2206 and E2101 |          |                    |                    |          |                    |                    |          |                    | Eq.         |
|---|---|----------|--------------------|--------------------|----------|--------------------|--------------------|----------|--------------------|-------------|
|   | E2006   |          |                    | E2206              |          |                    | E2101              |          |                    |             |
| Fuel                                      | Charcoal  | Plastics |                    | Charcoal           | Plastics |                    | Charcoal           | Plastics |                    |             |
|   | M <sub>c</sub> /kg                                |          | M <sub>H</sub> /kg | M <sub>c</sub> /kg |          | M <sub>H</sub> /kg | M <sub>c</sub> /kg |          | M <sub>H</sub> /kg |             |
|   | 1.5327  | 0.1104   | 0.2208             | 1.68               | 0.1693   | 0.3386             | 1.85               | 0.2044   | 0.4088             | 9.25 – 9.30 |
| O <sub>2</sub> R                          | 4.0923  | 0.2948   | 1.824              | 4.4856             | 0.4520   | 2.7088             | 4.9395             | 0.5457   | 3.2704             |             |
| TA  | 19.4653   | 1.4021   | 8.3904             | 21.336             | 2.1501   | 12.8668            | 23.495             | 2.5959   | 15.5344            |             |
| CO <sub>2</sub> P                         | 5.625   | 0.4052   | -----              | 6.1656             | 0.6213   | -----              | 6.7895             | 0.7501   | -----              |             |
| NRCO <sub>2</sub><br>(kg/ton)<br>Plastics |   | 1223     |                    |                    | 1223     |                    |                    | 1223     |                    |             |
| RCO <sub>2</sub><br>(kg/ton)              | 3670  |          |                    | 3670               |          |                    | 3670               |          |                    |             |
| SP (kg)                                   |   |          | 1.9872             |                    |          | 3.0474             |                    |          | 3.6792             |             |

NB:

- Total mass [M (kg)] of charcoal (M<sub>c</sub>) and plastic (M<sub>p</sub>) used gives total energy
- Oxygen required (O<sub>2</sub>R); Total air demand (TA); Carbon dioxide produced (CO<sub>2</sub>P); Non-Renewable carbon dioxide produced per tonne of PE plastic (NRCO<sub>2</sub>); Renewable carbon dioxide (RCO<sub>2</sub>); and Steam produced (SP)

Mass of CO<sub>2</sub> produced by charcoal or carbon of mass (M<sub>c</sub>) and plastics (PE) containing 33% carbon with  $k = 3.67$  (where  $k$  is a constant) is given by equation 9.29. Mass of oxygen required and air for combustion of the charcoal or carbon is obtained when  $k = 2.67$  for oxygen and  $k = 12.7$  for air.

Mass of oxygen required to burn hydrogen of mass (M<sub>H</sub>) to produce steam is given by equation 9.30 where  $k = 8$  for oxygen required and  $k = 9$  for steam produced.

$$\text{Mass of oxygen required or steam produced} = kM_H \dots\dots\dots 9.30$$

### 9.7.1 Assessing Carbon Dioxide Emissions and Sequestration

To estimate forest biomass which refers to the total amount of aboveground living organic matter in trees expressed as oven-dry tons per unit area requires knowledge of:

- Volume-weighted average wood density for oven-dry biomass per m<sup>3</sup> of green volume (WD)
- Biomass expansion factor which is ratio of aboveground oven-dry biomass of trees to oven-dry biomass of inventoried volume (BEF)

- Volume over back which is inventoried volume to a minimum tree diameter of 10cm (VOB)

Hence, According to FAO Corporate Document Repository (1997),

$$\text{Above ground biomass density (t/ha)} = \text{VOB} \times \text{WD} \times \text{BEF} \dots \dots \dots 9.31$$

Considering a tropical broadleaf forest with a VOB = 300 m<sup>3</sup>/ha and weighted average wood density (WD) = 0.65 t/m<sup>3</sup> and biomass expansion factor (BEF) = 1.74 gives (Eq. 9.31):

A biomass of VOB = 300 m<sup>3</sup>/ha x 0.65 t/m<sup>3</sup> = 194 t/ha, and  
 Above ground biomass density = 1.74 x 300 x 0.65 = 338 t/ha

Using one ton of polyethylene containing 33% of carbon produces 46,600MJ of energy and 1211.1kg of CO<sub>2</sub>. According to Sathre and O'Connor (2010), one ton of oven-dry matter per m<sup>3</sup> with moisture content of 15% to mass of (domestic) wood contains about 50% carbon and will produce 10,000MJ of energy on burning.

Hence, applying Eq. 29,

Carbon dioxide produced per ton of wood = 3.67 x 50% x 1000kg = 1835kg of CO<sub>2</sub>

Carbon dioxide produced per ton of PE = 3.67 x 33% x 1000kg = 1211.1kg of CO<sub>2</sub>

Wood saved by using one ton of PE = (1000kg x 46600MJ)/10000MJ = 4660kg

Mass ratio of wood to PE is 4.6:1 (approximately 5:1).

Table 9.8 Analysis of carbon dioxide emission and sequestration

| Characteristics   | 1 ton of PE | 1 ton of wood | Wood to produce 46600MJ |
|---|-------------|---------------|-------------------------|
| Mass (kg)   | 1000        | 1000          | 4660                    |
| Mass of Carbon  | 333         | 500           | 2330                    |
| Energy release (MJ)   | 46600       | 10000         | 46600                   |
| CO <sub>2</sub> produced (kg)   | 1211.1      | 1835          | 8551.1                  |
| Wood saved by using 1ton of PE (kg)   | -----       | -----         | 4660                    |
| Mass ratio of CO <sub>2</sub> produced  | 1           | 1.5           | 7                       |
| Area of forest saved (m <sup>2</sup> )  | -----       | 30            | 140                     |
| Biomass stalk created (kg)  | 825.75      | -----         | -----                   |
| <b>Net CO<sub>2</sub> reduction (kg) when 1ton of PE replaces wood = 8551.1 + 1211.1 = 9762.2kg which is stored in biomass stalk (Carbon sequestration)</b> |             |               |                         |

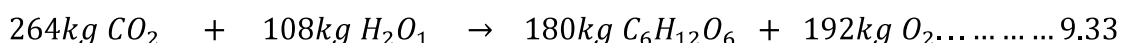
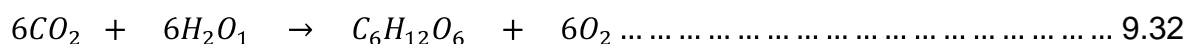
Mass ratio of CO<sub>2</sub> produced from wood to PE is 1.5: 1 which means one ton of wood produces 1.5 times the CO<sub>2</sub> produced by one ton of PE).

CO<sub>2</sub> release from wood to produce 46600MJ as from one ton of PE = (1835kg x 46600MJ)/10000MJ = 8551.1kg of CO<sub>2</sub>.

CO<sub>2</sub> production ratio for PE to wood to produce 46600MJ is 1:7 (8551.1/1211.1), which means to produce 46600MJ of energy from wood releases seven (7) times the CO<sub>2</sub> produced when the same amount of energy is released from PE.

Considering a tropical forest with aboveground biomass density of 338 t/ha, forest saved by using one ton of PE to get 46600MJ = (1ha x 4.66t)/338t = 0.014ha = 140m<sup>2</sup>.

Biomass accumulation in forest (biomass pools) depends on the photosynthesis process that withdraws CO<sub>2</sub> from the atmosphere.



1211.1kg of CO<sub>2</sub> from PE will produce (180kg x 1211.1kg)/264kg = 825.75kg of biomass stalk.

Hence, using high calorific waste (plastics) in energy efficient technology to replace wood provides multiple benefits. Saving the forest increases CO<sub>2</sub> sequestration potential with increase biomass accumulation. While one ton of PE provides 46.6 MJ compared to wood with 10MJ, it saves a forest of 140m<sup>2</sup> with biomass density of 338 t/ha while saving net CO<sub>2</sub> of 9762.2kg (Table 9.10).

## Chapter Ten

### Managing Environment, Safety and Risk Issues

#### 10.0 Analogy of Energy and Material Transformations

Careful analyses of the energy and mass balances based on the law of conservation of mass and energy reveal that input masses of plastic and charcoal undergo thermal transformation leading to output masses and energy. This transformation involves heat generation and transfer (gain or storage and losses) through conduction and convection with impacts on the process risk and safety state. Analysing the pyrolysis and exhaust gases within a cost-benefit assessment is essential to establishing a cost-effective environmental impact of the PG technology.

#### 10.1 Comparative Analysis of Waste Gases

Table 10.1 Exhaust gas properties for energy production plants

| Property                                       | Analytical method | Waste gas from existing plant |            | Waste gas from PGP                               | Waste gas from CG   |            |
|--|-------------------|-------------------------------|------------|--|---------------------|------------|
|  |                   | Analytical data               | Regulation | Analytical data                                  | Analytic data       | Regulation |
| Fuel used                                      |                   | Distilled light oil & off-gas |            | Mixed waste plastics                             | Distilled heavy oil |            |
| Dust (6%O <sub>2</sub> ) (g/Nm <sup>3</sup> )  | JIS Z8808         | < 0.001                       | < 0.15     | Requires analysis but does not apply for PE only |                     |            |
| Dust (13%O <sub>2</sub> ) (g/Nm <sup>3</sup> ) | JIS Z8808         |                               |            |  | 0.02                | < 0.10     |
| SO <sub>x</sub> (ppm)                          | JISK0103          | < 14                          | < 322      |  | 2                   | < 98       |
| NO <sub>x</sub> (6%O <sub>2</sub> ) (ppm)      | JIS B7982         | 111                           | < 150      |  |                     |            |
| NO <sub>x</sub> (13%O <sub>2</sub> ) (ppm)     | JIS B7982         |                               |            |  | 850                 | < 950      |
| HCl (12%O <sub>2</sub> ) (mg/Nm <sup>3</sup> ) | JIS K0107         | < 3                           | < 49       |  |                     |            |
| HCl (13%O <sub>2</sub> ) (mg/Nm <sup>3</sup> ) | JIS K0107         |                               |            |  | 1.3                 |            |
| DXN (ng TEQ/Nm <sup>3</sup> )                  | WHO-TEF           | 0.0026                        |            | 0.023  |                     |            |

Source: Adapted from Okuwaki et al. 2006

Efficient handling of the pyrolysis-synthesis gas mixture with effective burning produces mainly CO<sub>2</sub> and H<sub>2</sub>O. In large-scale application, exhaust gases may require basic scrubbing to remove flying ash from burning charcoal. Analysing and testing exhaust gas for acidic gases (NO<sub>x</sub>, SO<sub>x</sub>, HCl) from mixed plastic waste is required. Use of pure hydrocarbon plastics does not need acidic gas analysis. However, application of mix plastics must ensure that acidic gas concentration levels (If applicable) are within required threshold values (Table 10.1).



## 10.2 Results of the Pyrolysis and Exhaust Gas Analysis

Figure 10.1 shows collection of pyrolysis gas samples, containers used for pyrolysis and exhaust gases and temperature measurement. Analysis of the samples showed GC-MS chromatograms for the pyrolysis and exhaust gases. Comparison of the pyrolysis gas with VOC standard (VOX Mix 20, Ehrenstorfer, Germany) and with the NIST mass spectral library revealed the compounds (Appendices I and II). The compounds identified match in both retention time and mass spectra with the standard substances. No VOCs could be detected in the exhaust gas (Figures 10.2, 10.3 and 10.4).



Figure 10.1 Gas jars and gas bag used for collecting exhaust and pyrolysis gases

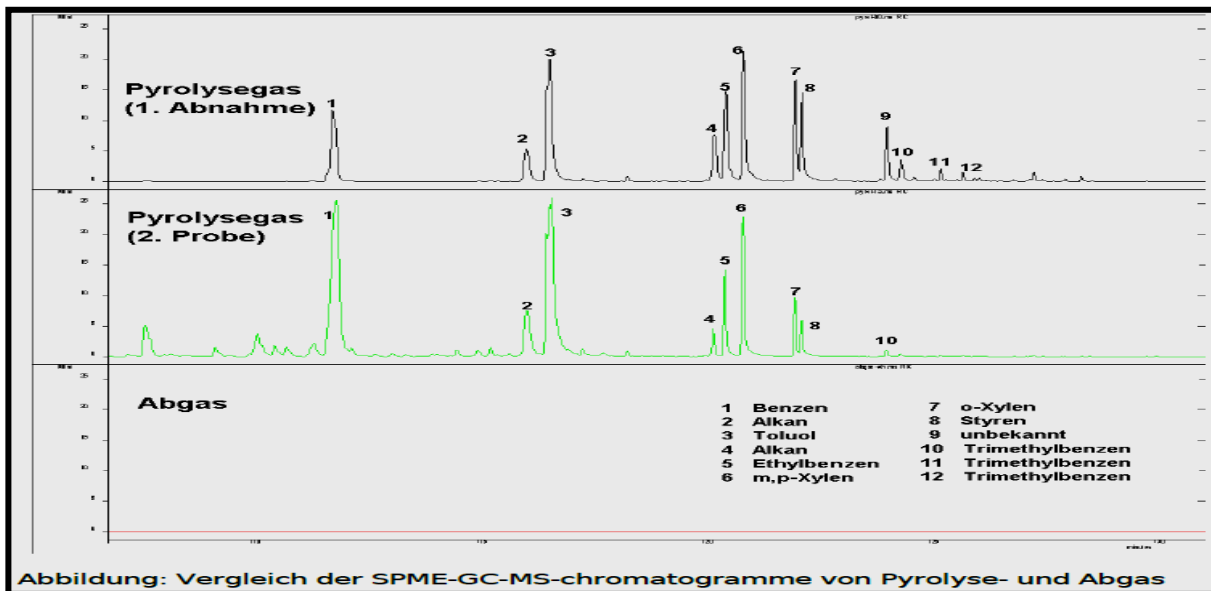


Figure 10.2 SPME-GC-MS-Chromatogram for pyrolysis and exhaust gas samples

The GC-MS chromatograms for exhaust gases (Abgas) samples collected during "normal", "excess" and "optimal combustion" are shown in figures 10.3 and 10.4. Figure

10.4 shows 4 exhaust gas samples in 4 different containers with a 4th contaminated (control sample) by benzene and toluene. The presence of benzene and toluene in both containers indicate contamination since these same containers were earlier used for the collection of the pyrolysis gas samples and was not well cleaned (Fig. 10.4).

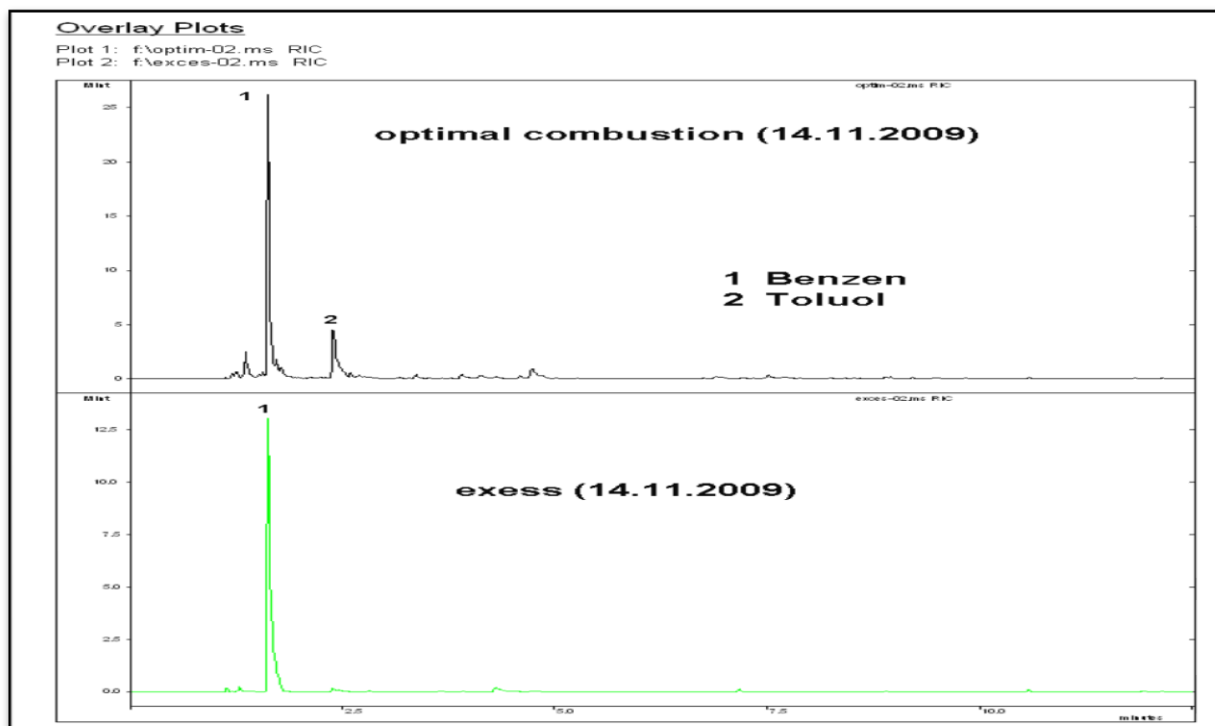


Figure 10.3 SPME-GC-Chromatogram for pyrolysis and exhaust gas samples

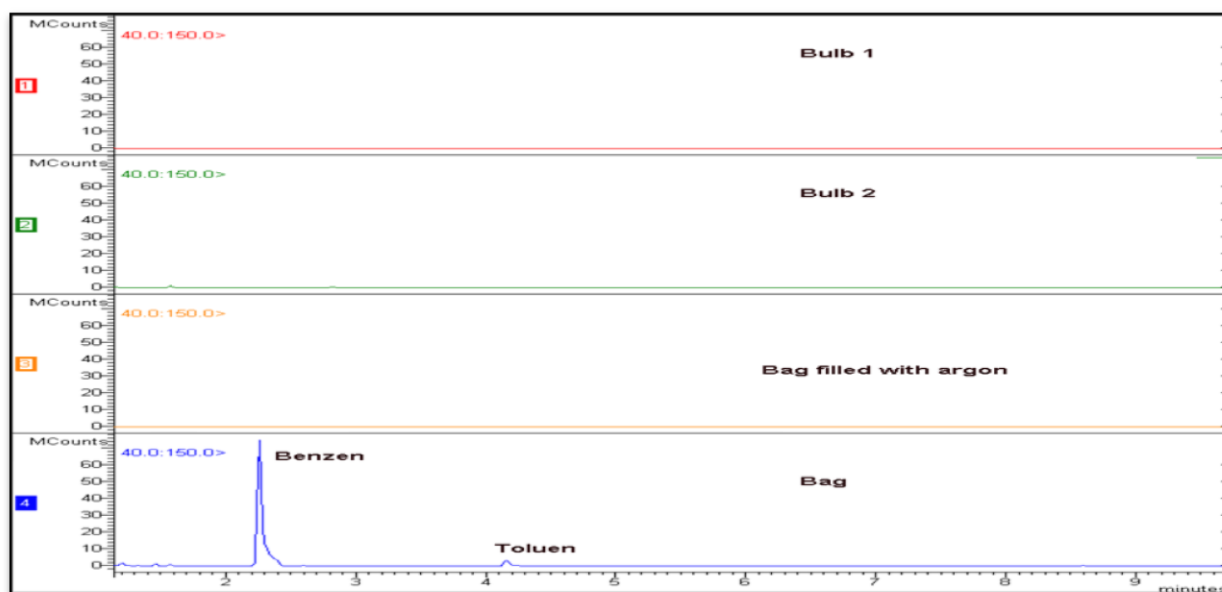


Figure 10.4 SPME-GC chromatographs for four exhaust gas samples

### 10.2.1 Combustibility of Pyrolysis Gases and Safety Impact Assessment

Table 10.2 presents the concentration and tolerance levels of major elements and compounds found in the ash, charcoal and PG chamber coke residues. The low mineral content of the ash makes it suitable as soil supplement.

Table 10.2 Identification, concentrations and tolerance level of chemicals in ash

| Substance                          | Sample 1     |                 | Sample 2      |                 | Sample 3    |                 | Sample 4    |                 |
|------------------------------------|--------------|-----------------|---------------|-----------------|-------------|-----------------|-------------|-----------------|
|                                    | Conc. /M-%   | Tolerance level | Conc. /M-%    | Tolerance level | Conc. /M-%  | Tolerance level | Conc. /M-%  | Tolerance level |
| <b>Na</b>                          | <b>0.41</b>  | 0.005           | <b>nn</b>     | 0.005           | <b>0.42</b> | 0.004           | <b>0.02</b> | 0.006           |
| <b>MgO</b>                         | <b>3.23</b>  | 0.008           | <b>nn</b>     | 0.008           | <b>0.48</b> | 0.003           | <b>1.28</b> | 0.006           |
| <b>Al<sub>2</sub>O<sub>3</sub></b> | <b>3.01</b>  | 0.004           | <b>0.89</b>   | 0.005           | <b>2.00</b> | 0.003           | <b>0.71</b> | 0.002           |
| <b>SiO<sub>2</sub></b>             | <b>11.12</b> | 0.011           | <b>4.65</b>   | 0.012           | <b>9.70</b> | 0.008           | <b>4.17</b> | 0.006           |
| <b>P<sub>2</sub>O<sub>5</sub></b>  | <b>2.13</b>  | 0.003           | <b>0.18</b>   | 0.004           | <b>0.50</b> | 0.001           | <b>1.13</b> | 0.002           |
| <b>SO<sub>3</sub></b>              | <b>0.95</b>  | 0.002           | <b>0.04</b>   | 0.004           | <b>0.48</b> | 0.001           | <b>0.66</b> | 0.002           |
| <b>Cl</b>                          | <b>1.95</b>  | 0.002           | <b>0.18</b>   | 0.001           | <b>2.00</b> | 0.001           | <b>0.47</b> | 0.001           |
| <b>K<sub>2</sub>O</b>              | <b>4.50</b>  | 0.007           | <b>0.04</b>   | 0.005           | <b>0.37</b> | 0.002           | <b>2.84</b> | 0.003           |
| <b>CaO</b>                         | <b>16.24</b> | 0.013           | <b>0.47</b>   | 0.005           | <b>3.81</b> | 0.005           | <b>9.92</b> | 0.006           |
| <b>TiO<sub>2</sub></b>             | <b>0.59</b>  | 0.002           | <b>0.12</b>   | 0.002           | <b>1.74</b> | 0.002           | <b>0.11</b> | 0.001           |
| <b>Cr<sub>2</sub>O<sub>3</sub></b> | <b>0.02</b>  | 0.001           | <b>0.05</b>   | 0.002           | <b>0.01</b> | 0.002           | <b>nn</b>   | 0.001           |
| <b>Mn<sub>2</sub>O<sub>3</sub></b> | <b>1.67</b>  | 0.002           | <b>0.69</b>   | 0.003           | <b>0.04</b> | 0.002           | <b>1.56</b> | 0.001           |
| <b>Fe<sub>2</sub>O<sub>3</sub></b> | <b>10.49</b> | 0.005           | <b>107.44</b> | 0.038           | <b>3.99</b> | 0.002           | <b>0.49</b> | 0.001           |
| <b>Cu</b>                          | <b>0.04</b>  | 0.001           | <b>0.07</b>   | 0.002           | <b>0.05</b> | 0.002           | <b>0.01</b> | 0.001           |
| <b>Zn</b>                          | <b>0.27</b>  | 0.001           | <b>0.06</b>   | 0.003           | <b>1.10</b> | 0.001           | <b>0.03</b> | 0.001           |
| <b>Br</b>                          | <b>0.01</b>  | 0.003           | <b>1.41</b>   | 0.025           | <b>nn</b>   | 0.001           | <b>nn</b>   | 0.001           |

### 10.2.2 Identification of Risks Linked to the PG Process

System efficiency will be increased by analysing equipment failures, human-machine-process interactions, manual and automated control system design and root causes of failures during large scale operation. Hence, optimising system design, installation, control, start-up and shut-down operations and maintenance is required. Emphasis is laid on safety requirements, time management, reliability, energy-use efficiency and minimization of operating costs. Potential risks identified with mitigation strategies linked to the PG technology are summarized in table 10.4.

The design is made simple with few operating parts to enhance easy maintenance and replacement of higher risk related components e.g. the PG chamber and hot gas transmission pipes and the combustion chamber.

Table 10.3 Identification, prevention and mitigation of potential risks

| Potential risks   | Integrated preventive and mitigation measures   |
|---|---|
| Explosion in PG chamber   | <ul style="list-style-type: none"> <li>✓ A double metal layer system is installed with potential to readily replace external pipe after long term usage</li> <li>✓ PG chamber is made of thicker metals with a safety vent to reduce any potential explosion risk</li> <li>✓ In the event of an explosion, safety valve breaks releasing pyrolysis gas into the casing which is discharged through the chimney</li> <li>✓ PG chamber and hot gas transmission pipes and the combustion chamber are easy to dismantle, repair and to replace separately or at same time while other system parts could be used for long periods</li> </ul> |
| Pollution due to back-flow of pyrolysis gas                           | <ul style="list-style-type: none"> <li>✓ Control of continuous loading to optimise supply rate and conversion of the plastics to gaseous products with high combustion efficiency is possible</li> <li>✓ Continuous loading reduces the amount of pollution in the event of an explosion</li> <li>✓ Application of improved spiral loading increases compaction and reduces gaseous back-flow through loader</li> </ul>   |
| Increase discharge of CO <sub>2</sub> , acidic gases and heavy metals | <ul style="list-style-type: none"> <li>✓ Complete and stoichiometric combustion is optimized in burning charcoal</li> <li>✓ Most of CO<sub>2</sub> produced is used by forest saved (carbon sink)</li> <li>✓ No release of unburned pyrolysis-synthesis gases or VOCs</li> <li>✓ Heavy metals and other polluting gases are trapped in burning charcoal</li> </ul>  |

### 10.3 Why Formation of PCDD/Fs (dioxins) is Impossible

A major strength of the PG technology involves the absence of the release of VOCs and PCDD/Fs (dioxins) which distinguishes the process from incinerations. Dioxins are formed during burning and pyrolysis of some raw materials which contains carbon, hydrogen, oxygen, chlorine and catalysts (Yasuhara et al., 2005). This oxidation in molecular oxygen occurs between 600-700°C especially in the combustion of MSW, waste car oil, fuel in power plants and internal combustion engines. Other sources include steel foundries, woodworking enterprises, pesticides and herbicides.

**Combustion in the PG system:** PG system operates based on similar chemical processes in incineration systems. However, the organic feedstock (plastic or wood) is heated by an initial energy source (Fig. 10.5). No VOCs have the possibility to escape glowing charcoal with resulting ash scavenges any combustible molecules including acidic gases and heavy metal.

### 10.3.1 Modelling Physico-chemical Processes of Incineration and PG Process

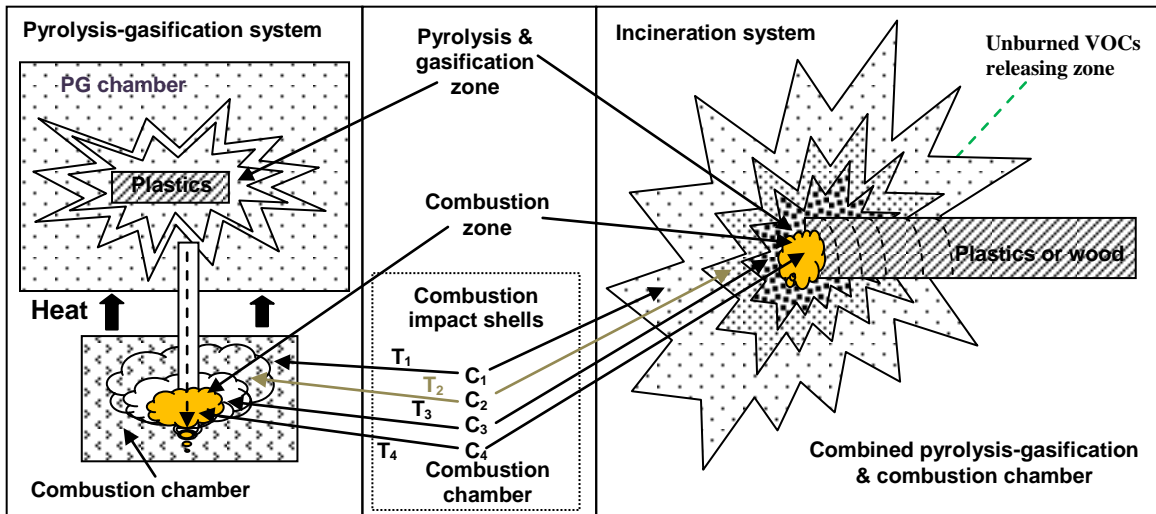


Figure 10.5 Modelling physico-chemical process of combustion systems

**Combustion in the incineration system:** The plastic or wood is heated by an external initial flame on one end until ignition and burning occurs. The organic polymers at ignition point breakdown releasing VOCs which mix with oxygen and burn directly. This heats the wood or plastic piece within decreasing temperatures across varied combustion impact shells. VOCs released out of the flame zone are cooled with the potential of creating various molecular groups in the presence of molecular oxygen as they flow through C<sub>4</sub> to C<sub>1</sub> with T<sub>4</sub> - T<sub>1</sub> respectively.

This explains why the PG technology produces no pollutant organic molecules and requires no secondary burner compared to incineration systems. Although acidic gases and heavy metals in exhaust gases and ash residue needs to be monitored in large scale application with mixed plastic waste, using PE and charcoal offers very little or no related risks. Pyrolysis of mixed plastics results in overlapping of organic matter with synergies of materials, drying of absorbed water and pyrolysis of mineral matter at higher temperature (Aboulkas et al., 2007).

## Implications and Utilisation of Research Results

## Chapter Eleven

## Implications and Utilisation of the PG Technology

## 11.0 Benefits and Incentives of Developing the PG Technology

The development of the PG technology to transform plastic waste to energy improves human welfare, sustainable development, energy efficiency and environment. The interconnectivity between the goals summarizes the implications and utilization of the technology in producing alternative energy to wood in most communities (Fig. 11.1).

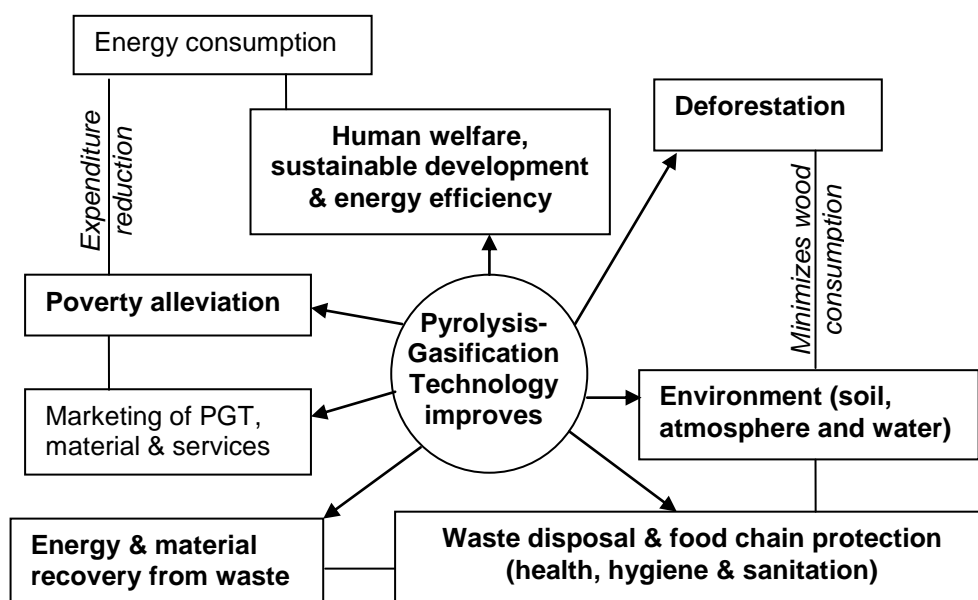


Figure 11.1 Impacts of the pyrolysis-gasification technology

Developing this technology advances knowledge in the field of energy production technology especially from waste with special emphasis on plastic waste. Plastic waste has been a very difficult to handle waste in all communities globally. However, this technology is innovative in its cost-effectiveness and adaptation to socioeconomic and environmental constraints. The inability to overcome such constraints has been a major hindrance to plastic waste recycling resulting in significant health, hygiene and sanitation problems to humans and biodiversity. Using the PG technology solves many

problems linked to waste disposal and energy production offering the following advantages:

1. Recovery of non-recyclable waste plastics and high calorific waste
2. Production and marketing of the technology for small, medium and large scale application
3. Improving material and energy recovery from waste
4. Integration of indigenous and modern techniques driven by incentives in cost-effective waste management

### **11.1 Impacts, Implication and Utilization of the Primary Data**

Successful production and marketing of this technology depends on its acceptability based on fuel or feedstock quality and availability. This underpinned the need to conduct waste analysis in Cottbus in Germany (developed country) and Lagos in Nigeria (developing country). Effective waste management must consider waste properties, local realities and impacts in order to design mitigation measures (appendix VII). The variations in the composition and quality of the waste indicate that material and energy recovery management strategies must be adapted to waste characteristics.

### **11.2 Cost-benefit Analysis (CBA) of the PG Technology**

The handling of multiple socioeconomic and environmental concerns linked to the waste-to-energy processes and technologies vis-à-vis climate change and emission control offers inherent cost and benefits. The development and utilization of the PG technology involved an environmental cost resulting from the production of CO<sub>2</sub>. This cost is mitigated through carbon sequestration by the saved forest when wood is replaced by plastic waste. Other cost, benefits and mitigation measures have been summarized in table 11.1 and figure 11.1. Though CBA has been done qualitatively, quantitative evaluation will be conducted in further studies during real world application of the PG technology.

Table 11.1 Evaluating cost-benefits analysis (CBA) of the PG system

|               | Costs   | Benefits  |
|---------------|---|---|
| Economic      | <ul style="list-style-type: none"> <li>• Highly demanding research involving concept formation, design, constructions &amp; optimization and waste &amp; feedstock analysis</li> <li>• Relatively high equipment, material, labour &amp; electricity cost for single unit construction</li> </ul> | <ul style="list-style-type: none"> <li>• Waste plastics is abundant and free</li> <li>• Motivates manual sorting of mixed waste and to get plastics</li> <li>• Technological production requires limited resources while creating jobs</li> <li>• Research involved learning, innovative thinking, creativity and capacity building</li> <li>• Cost reduction for large scale production occurs when local materials are used</li> <li>• Integrating modern &amp; indigenous technology minimizes cost</li> <li>• Application of results creates long term socioeconomic and environmental benefits for global sustainable development</li> </ul> |
| Social        | <ul style="list-style-type: none"> <li>• Difficulties involved in adapting to new technology</li> <li>• Market failures due to inefficiencies of balancing negative and positive externalities</li> </ul>   | <ul style="list-style-type: none"> <li>• Recovery of energy from plastics solves energy, health, sanitation, pollution &amp; city littering problems</li> <li>• Reduce landfill space, water &amp; ocean ecosystem pollution</li> <li>• Obtaining alternative energy from plastics saves forest and biodiversity while mitigating climate change</li> <li>• Offers pragmatic research with universal application in solving multiple contemporary problems</li> </ul>   |
| Environmental | <ul style="list-style-type: none"> <li>• Extra CO<sub>2</sub> and other emissions from plastics with fossil origin influences climate change</li> <li>• Plastic production emits potential harmful chemicals</li> </ul>   | <ul style="list-style-type: none"> <li>• High safety standards based on the precautionary and preventive action and correction principles is applied</li> <li>• Experiments performed under extreme conditions with limited funds out door in winter &amp; summer conditions</li> <li>• Improved insulation leads to high energy production and utilization efficiency</li> <li>• Enhances material and energy recovery from waste improving health, environmental and socioeconomic impacts</li> <li>• Recovery of non-degradable plastics saves landfill space</li> </ul>   |

### 11.2.1 Assessing the Willingness to Accept (WTA) and Willingness to Pay (WTP)

A survey was carried out on a random sample of 117 people in Lagos (Nigeria) and Porto-Novo (Benin) to assess the WTA and WTP for a PG technology. 98 respondents (83.77%) indicated their willingness to accept and pay for any safe and efficient technology that uses plastics as energy source given the menace caused by the waste fraction. 15 respondents (12.82%) rejected the idea because of uncertainty about the existence of such a technology which is often misconceived to be incineration. Finally, 4 respondents (3.41%) were undecided (Fig. 11.2). A wide



range of acceptance of the technology is observed for the following reasons:

- It offers cost-effective and environmentally friendly solution
- The technology is adaptable to a wide range of applications

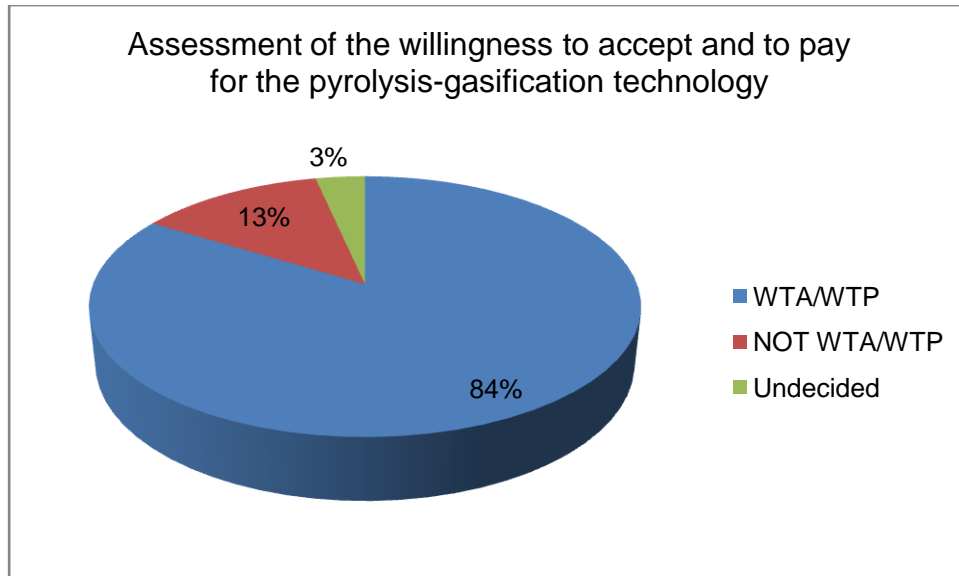


Figure 11.2 Assessments of WTA and WTP for the PG technology

Although there is a strong WTA and WTP, the PG technology needs a pilot project for producing, test-running and evaluating impacts at domestic, small, medium and industrial scale levels.

### 11.2.2 Environmental Impact Assessment (EIA) of the PG Technology

Attention was paid to environmental issues from pre-feasibility through construction to utilization stages. In the entire material and energy recovery process, mechanical recycling is preferred with thermal recycling recommended as last option. However, thermal recycling emphasizes pollution control and prevention, waste minimization and cleaner energy production as follows.

Emission, health, risk and safety are sufficiently addressed with mitigation and abatement measures proposed. Residual impacts such as from waste ash were evaluated and observed to have minimum impacts. Strategic environmental assessment (SEA) is recommended for any large scale application of the PG technology with maximization of energy-use and profits.

### 11.2.3 Density and Temperature Variations

The air density in the oven, combustion chamber, chimney and surrounding will always vary based on their temperature. Air will always flows from region of higher to lower density. Hence, cold high-density air soaked into the systems due to internal-external pressure difference is heated in the combustion chamber as oxygen is used. The exhaust gases expand upwards and the only outlet is the chimney.

|   |  |
|---|--|
| Natural draft in chimney: $\partial P_{chim} = (\rho_o - \rho_i)hg$                                     |  |
| Density of medium: $\rho_m = \frac{\rho_o T_o}{T_o + T}$  |  |
| $\rho_o > \rho_{out} > \rho_{chim} > \rho_{com}$  | $\partial P_{com} > \partial P_{chim} > \partial P_{out} > \partial P_o$ |
| NB: Air intake into the stove is one-directional with release of exhaust gases only through the chimney |  |

Figure 11.3 Trend in air density and pressure variations

Figure 11.3 presents the trend in air density (decreasing order) and pressure variation (increasing order) as function of temperature from normal atmospheric to combustion chamber. Table 11.2 shows the values of air density (decreasing order) and pressure variation (increasing order) as function of temperature from normal atmospheric to combustion chamber.

Table 11.2 Values of air density and pressure variation as a function of temperature

|                               | $P_s/\text{kgm}^{-3}$ | $T_s/^\circ\text{K}$ | $T_i/^\circ\text{C}$ | $\rho_o/\text{kgm}^{-3}$ | $\partial P$ |
|-------------------------------|-----------------------|----------------------|----------------------|--------------------------|--------------|
| $\rho_o$ at $0^\circ\text{C}$ | 1.293                 | 273                  | 0                    | 1.293                    | 0            |
| $\rho_{com}$                  | 1.293                 | 273                  | 467                  | 0.477                    | 20.012       |
| $\rho_{chim}$                 | 1.293                 | 273                  | 345                  | 0.571                    | 17.707       |
| $\rho_{out}$                  | 1.293                 | 273                  | 20                   | 1.205                    | 2.158        |

### 11.3 Financial Cost of the PG Technology

The models were constructed using various materials and local labour. Application of local and modern technologies and materials influenced the various costs. This makes comparison of the cost of labour and materials which influence quality of the various models difficult (Table 11.3).

Table 11.3 Comparison of the cost and qualities of the various PG models

| Country                         | Model description  | Materials used   | Cost /€   |
|---------------------------------|--|--|-----------|
| Germany<br>(Most optimized)     | PG chamber is connected to the combustion chamber using protected multiple metal layer gas transfer pipe. Primary & secondary air inlet with single exhaust gas outlet. Insulated casing with Al-silicate wool | Iron plates, sheets & pipes for construction and glass and Al-silicate wool for insulation | 2000-3000 |
| Cameroon<br>(Optimized model 1) | PG chamber connected by two single layer pipes to combustion chamber. Single air inlet and outlet. Insulated casing with glass wool  | Iron plates, pipes; sand, earth & sawdust mixture as insulation material                   | 75-150    |
| Nigeria<br>(Optimized model 2)  | PG chamber combined with gas connection pipe. Primary & secondary air inlet with single exhaust gas outlet. Insulated casing with sand, saw dust and earth mixture.  | Iron plates, pipes & sawdust, sand and earth mixture for insulation                        | 50-120    |

#### 11.4 Small-scale Execution of RESA in Waste and Plastic Waste Recovery

RESA sorting line uses mainly human labour for sorting. The waste from the city is delivered at the dumpsite. The waste is passed over (arrow direction) riddle screen (A) to remove fine particles of  $\leq 60\text{mm}$  diameter (rich in organic and mineral compounds) for direct composting or anaerobically digested for biogas production (Fig. 11.4).

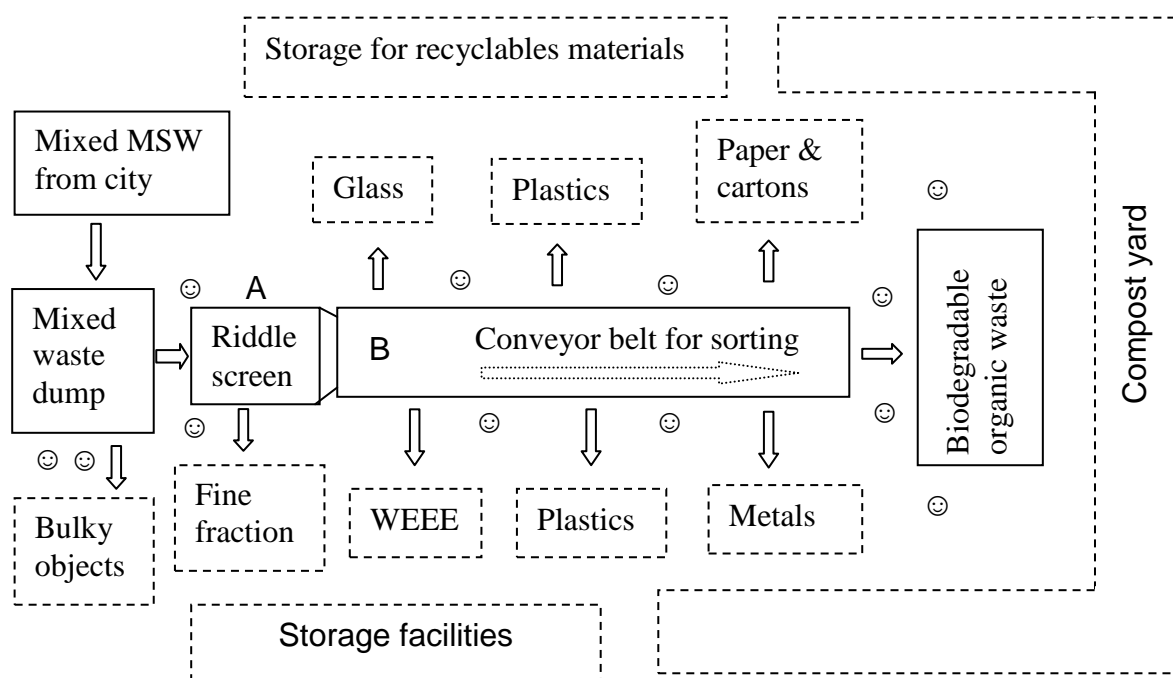


Figure 11.4 RESA based commingled waste sorting line and schematic plan

The course fraction is then passed through a conveyor belt (B) and sorted by protected persons (☺) manually to recover plastics and/or paper and cartoon for energy recovery; Metal, WEEE and glass for recycling, and rest of the organic fraction for composting.

### 11.5 Utilization of Research Results

This study was motivated by the desire to solve a waste management, environmental and energy problem common to all human societies. Hence the development of the pragmatic, scalable, replicable and sustainable technology using PG processes to produce energy from waste plastics.

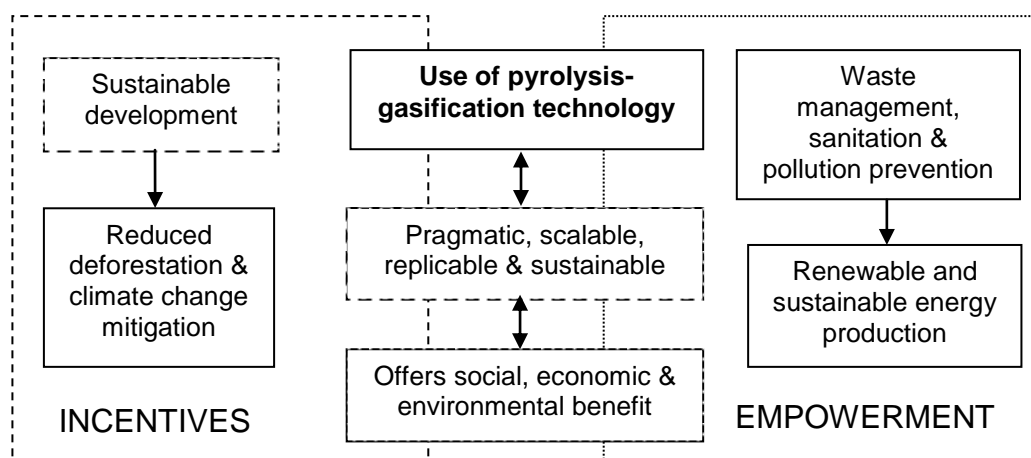


Figure 11.5 Contribution of PG technology to sustainable development

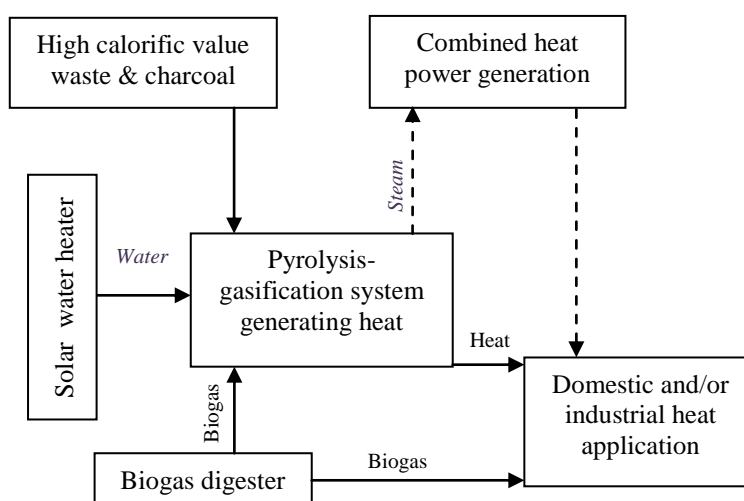


Figure 11.6 Integrated renewable energy production and utilization model

The application of this technology is driven by incentives for achieving sustainable development while mitigating climate change through reducing deforestation. Energy and materials recovery from waste can empower poor city dwellers while improving

health and sanitation (Fig. 11.5). The heat produced can be used to generate steam as energy transfer medium and collecting distilled water for laboratory and medical use. Same system can be used for biofuels or alcohol distillation (Fig. 11.6).

**11.5.1 The Integrated Energy, Waste Management and Agricultural Project**

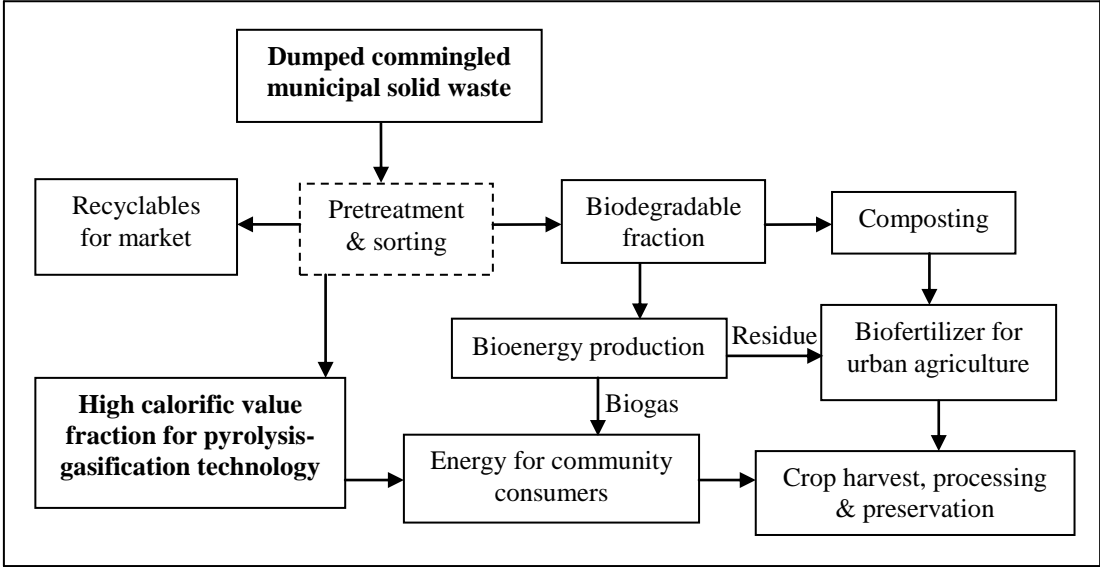


Figure 11.7 Sustainable energy, waste management and agricultural project model

The small or medium scale application of material and energy recovery from waste can be achieved within a sustainable energy, waste management and agricultural project. Effective commingled waste management involves sorting to obtain recyclable fraction for marketing or recycling while using high calorific waste for energy recovery. The biodegradable waste can be composted to manure for farming or anaerobically digested to biogas for bioenergy and manure production (Fig. 11.7). The energy produced can be used mainly as high valued heat (cooking and heating) and low valued heat for crop post-harvest treatment and preservation. This is a centralized system to improve efficiency of energy production and usage

## **Chapter Twelve**

### **Recommendations and Conclusion**

#### **12.0 Energy, Resource and Development Research**

Employing applied and process engineering in recovering energy and material resources from waste with maximum environmental protection is fundamental to sustainable development. A multidisciplinary perspective that integrates scientific and technological principles, human behavioural motivations and chemical interactions of materials (chemistry) is required. This study establishes the following facts and advances a set of RESA-based recommendations for improving waste management:

- PG technology is cost-effective, scalable, adaptable and replicable to demand
- Potential socioeconomic and environmental benefits are high but real impacts quantification need to be ascertained through pilot and field application
- Energy and material recovery from waste is essential to sustainable development and poverty alleviation
- Attending MDGs depends on the quality and quantity of energy-mix-services

#### **12.1 Effective Management of Emerging Waste and Plastics**

This thesis underscores the interconnectivity between waste management, role of scientific and technological research and sustainable development. Such interconnectivity integrates socioeconomic, environmental and industrial development concerns within the closed-loop sustainable production and consumption chain. Effective management of emerging waste especially within consumer economies of developing countries of Africa should emphasis:

- Permanent monitoring, evaluation and continuous improvement of waste management services
- A search for methods to integrate appropriate indigenous and modern waste technologies
- Promoting policy, action and implementation measures with potential of generalization
- Raise awareness and commitment to incentive-driven community waste management practices

## **12.2 Pragmatic Problem-solving Approach to Waste Management Challenges**

Applying a bottom-up approach to waste management is most appropriate to developing countries. This should consider emerging trends and issues such as:

- Urbanization caused by rural exodus and rapid population growth increases burden on environment and infrastructure
- Improvement of waste management infrastructure towards material and energy recovery reduces resource lost
- Marketing of material and energy resources from waste alleviates poverty while increasing landfill life span and reducing pollution
- Training and capacity building advances technology based on appropriate R&D
- Growing industrialization, urbanization and modernization increases waste generation and composition
- Legislation and education should gradually change human mind-set, lifestyle and consumption patterns towards waste reduction, recycling and reuse

## **12.3 Green Entrepreneurship and Resource Valorisation**

Effective waste management should vulgarize the marketing of recovered materials by creating business-driven incentives for secondary materials. Skilful manpower is required for treating the waste and producing waste transformation technologies. Hence, this study accomplishes:

- Propelling a paradigm shift towards recycling and reuse of recoverable materials locally empowering individuals, scavengers and green entrepreneurial initiatives
- Creating a competitive vibrant private sector underpinned by social, profit-driven and auto-regulatory mechanism
- Generating sustainable self-employment and business opportunities that alleviate poverty while improving human welfare, health and sanitation

Targeted incentive sources include government subsidies, sales of recovered items for reuse, recycling, compost for manure, biogas for energy production and waste disposal charges. Waste management should motivate public participation and marketing of recovered waste fractions based on their uses.

## **12.4 Conclusion**

Continuously evaluating and improving waste management systems is an ever on-going process. While waste management firms strive to achieve far reaching results in the

domain of hygiene and sanitation, they need to become more productive and profitable. Improving sanitary land filling of non-recyclables through waste reduction requires promotion of material and thermal recycling and reuse.

However, the concept of applying state-of-the-art and best waste management practices needs to be considered with caution because there is no ideal management style that works universally. Hence successful management is always adapted to relevant prevailing situational circumstances.

This is achievable only when decision-making processes are underpinned by relevant reliable data. Consequently, regular stock-taking of the human, material and financial resources and evaluating input-output balances is constantly required. The role and good-will to do 'the right things rightly' is also essential for effective management of public-goods and service.

#### **12.4.1 The Task Ahead of Waste Managers in Developing Countries**

Waste management in most developing world cities involves periodic clearing of refuse piles. This involves cleaning drainage systems to ensure continuous flow of surface run-offs, streets sweeping and clearing of refuse dumps. Educating and forcing the inhabitants to comply with environmental regulations and to participate in the ensuring of a clean environment offers a challenge. Hence, creating a multidisciplinary think-tanks group to design relevant policies and R&D programs and advice the authorities on waste management issues and projects will:

- Generate and manage a reliable database to underpin veritable decision-making towards modelling a cost-effective management system
- Design, elaborate and valorise basic pragmatic environmental protection rules and regulations that motivate material and energy recovery from waste
- Prepare and disseminate a comprehensive environmental education and awareness program for all levels of society

Technologies for transforming various waste streams (metal, putrescible, plastics, waste water and waste engines oils) to usable goods and services are required. This study divulges multiple opportunities of developing innovative disposal technologies and methodologies adapted to local realities. It invokes a behaviour change and awareness pattern of rethinking waste as a resource with wealth-cash value.



#### **12.4.2 Need for Further Research**

Though the PG technology offers a sustainable solution to the problems of waste plastics, further research will continuously improve its performance and efficiency. Hence, further research goal identified include:

1. Cost-effective scaling of technology to demand including evaluation of socioeconomic, cultural and environmental impacts in field studies
2. An economic evaluation of the PG technology and RESA in field situation involving forest saving with impacts on carbon trading and MDGs achievement
3. Integration of other renewable energy forms (solar hot water heater, biogas as co-fuel or initial fuel) in large scale application of the PG technology for distillation, dryer and baking
4. Impacts and complexities linked to profitable entrepreneurial application is needed to generate baseline data for large scale production and marketing

Such further research requires a corresponding budget and relatively longer time. This will form a major part of the inventor's waste-to-energy research career goals. All stated study objectives were accomplished with satisfactory outcomes despite any socioeconomic challenges faced. The PG technology offers a benign multiple package solution to waste plastics and energy problems. Applying the technology in real world is subject to continuous monitoring and evaluation for innovative improvement.

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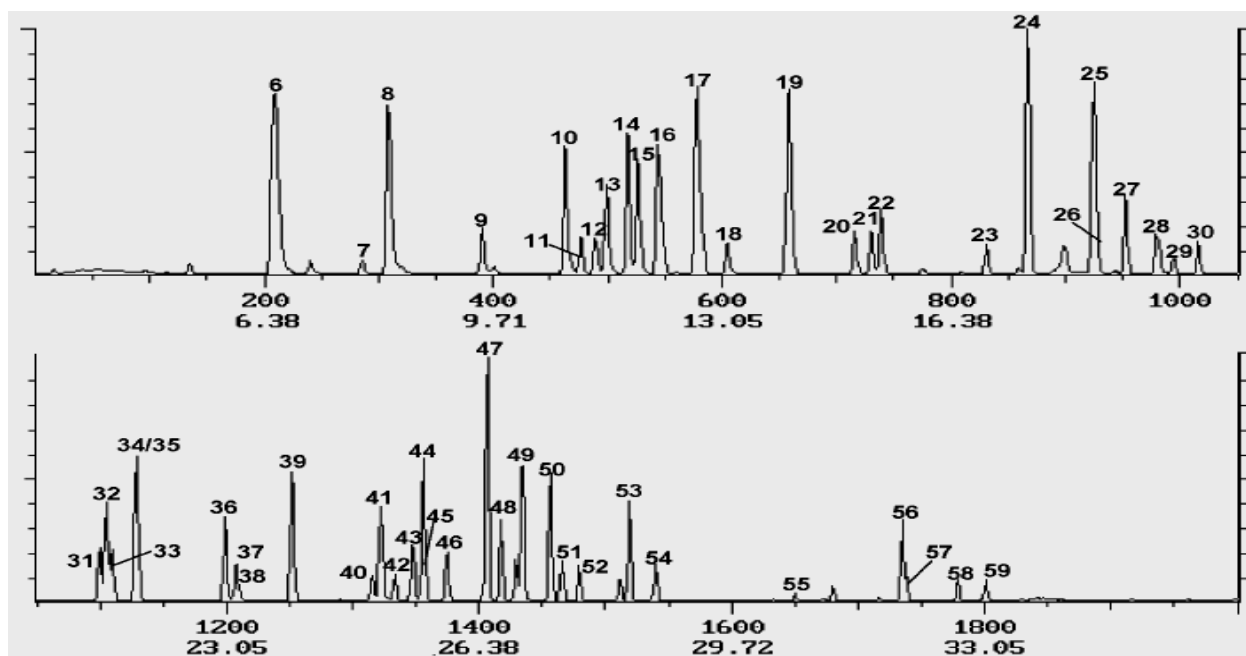
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## Appendices

### Appendix I: Spectra of 59 standard VOCs found in the NIST MS spectra database





## Appendix II: Mass charge ratio of 59 standard VOCs in the NIST MS spectra database

| No. | Peak  | Chemical name or formula                               | M/z | No. | Peak  | Chemical name or formula                   | M/z |
|-----|-------|--|-----|-----|-------|--|-----|
| 1   | 3.31  | CCl <sub>2</sub> F <sub>2</sub>                        | 85  | 31  | 21.37 | Chlorobenzene                              | 112 |
| 2   | 3.98  | CH <sub>2</sub> =CHCl                                  | 62  | 32  | 21.48 | Ethylbenzene                               | 91  |
| 3   | 4.63  | CH <sub>3</sub> Br                                     | 94  | 33  | 21.55 | CCl <sub>3</sub> -CH <sub>3</sub>          | 131 |
| 4   | 4.96  | CH <sub>2</sub> Cl-CH <sub>3</sub>                     | 34  | 34  | 21.88 | m-Xylene                                   | 91  |
| 5   | 5.28  | CCl <sub>3</sub> F                                     | 101 | 35  | 21.88 | p-Xylene                                   | 91  |
| 6   | 6.53  | CCl <sub>2</sub> =CH <sub>2</sub>                      | 36  | 36  | 23.02 | o-Xylene                                   | 91  |
| 7   | 7.78  | CH <sub>2</sub> Cl <sub>2</sub>                        | 84  | 37  | 23.17 | Styrene                                    | 104 |
| 8   | 8.20  | t-CHCl=CHCl  | 96  | 38  | 23.23 | Bromoform                                  | 173 |
| 9   | 9.55  | CHCl <sub>2</sub> -CH <sub>3</sub>                     | 83  | 39  | 23.92 | Isopropylbenzene                           | 105 |
| 10  | 10.78 | c-CHCl=CHCl  | 96  | 40  | 24.98 | Bromobenzene                               | 156 |
| 11  | 10.98 | CH <sub>3</sub> -CCl <sub>2</sub> -CH <sub>3</sub>     | 97  | 41  | 25.10 | n-Propylbenzene                            | 91  |
| 12  | 11.20 | CH <sub>2</sub> BrCl                                   | 130 | 42  | 25.27 | CHCl <sub>2</sub> -CHCl <sub>2</sub>       | 83  |
| 13  | 11.36 | CHCl <sub>3</sub>                                      | 83  | 43  | 25.50 | 2-Cl-toluene                               | 126 |
| 14  | 11.6  | CCl <sub>4</sub>                                       | 117 | 44  | 25.63 | CH <sub>2</sub> Cl-CHCl-CH <sub>2</sub> Cl | 75  |
| 15  | 11.83 | CCl <sub>3</sub> -CH <sub>3</sub>                      | 97  | 45  | 25.63 | 1,3,5-Trimethylbenzene                     | 105 |
| 16  | 12.13 | CCl <sub>2</sub> =CH <sub>2</sub> -CH <sub>3</sub>     | 110 | 46  | 25.97 | 4-Cl-toluene                               | 126 |
| 17  | 12.63 | Benzene  | 78  | 47  | 26.48 | t-Buthylbenzene                            | 119 |
| 18  | 13.13 | CH <sub>2</sub> Cl-CH <sub>2</sub> Cl                  | 62  | 48  | 26.48 | 1,2,4-Trimethylbenzene                     | 105 |
| 19  | 14.01 | CHCl=CCl <sub>2</sub>                                  | 130 | 49  | 26.97 | Sec-Buthylbenzene                          | 105 |
| 20  | 14.98 | CH <sub>2</sub> Br <sub>2</sub>                        | 174 | 50  | 27.32 | p-Isopropylbenzene                         | 119 |
| 21  | 15.23 | CH <sub>2</sub> Cl-CHCl-CH <sub>3</sub>                | 76  | 51  | 27.48 | 1,3-Dichlorobenzene                        | 146 |
| 22  | 15.36 | CHBrCl <sub>2</sub>                                    | 129 | 52  | 27.70 | 1,4-Dichlorobenzene                        | 146 |
| 23  | 16.90 | c-CHCl=CH <sub>2</sub> -CH <sub>2</sub> Cl             | 110 | 53  | 28.37 | n-Buthylbenzene                            | 91  |
| 24  | 17.52 | Toluene  | 91  | 54  | 28.70 | 1,2-Dichlorobenzene                        | 146 |
| 25  | 18.47 | CCL <sub>2</sub> -CCl <sub>2</sub>                     | 166 | 55  | 30.53 | 1,2-Dibromo-3-chloropropane                | 157 |
| 26  | 18.52 | t-CHCl=CH <sub>2</sub> -CH <sub>2</sub> Cl             | 110 | 56  | 31.97 | Hexachlorobutadiene                        | 225 |
| 27  | 18.92 | CHCl <sub>2</sub> -CH <sub>2</sub> Cl                  | 97  | 57  | 32.02 | 1,2,3-Trichlorobenzene                     | 180 |
| 28  | 19.38 | CHBr <sub>2</sub> Cl                                   | 129 | 58  | 32.70 | Naphthalene                                | 128 |
| 29  | 19.62 | CH <sub>2</sub> Cl-CH <sub>2</sub> -CH <sub>2</sub> Cl | 76  | 59  | 33.08 | 1,2,4-Trichlorobenzene                     | 180 |

## Appendix III: Data collection tables and forms

### Table III-1: Water boiling test

| Tester's name                    |                     | Remarks | Entry                         | Value  |
|----------------------------------|---------------------|---------|-------------------------------|--------|
| Test Number                      | .....               |         | <b>Mass (cold start)</b>      |        |
| Date & location                  | .....               |         | Dry pot 1                     | .....g |
| Stove type/model                 | .....               |         | Pot 1 + water                 | .....g |
| Local b. pt. (°C)                | .....               |         | Pot 1 + water at first boil   | .....g |
| Sun/rain                         | .....               |         | Pot 1 + water after simmering | .....g |
| Air temperature                  | .....               |         | <b>Hot start: Dry pot 2</b>   | .....g |
| Wind conditions                  | .....               |         | Pot 2 + water                 | .....g |
| Time (min)                       | Start:.....End..... |         | Pot 2 + water at first boil   | .....g |
| Simmer time (Min)                | Start:.....End..... |         | Pot 2 + water after simmering | .....g |
| Starting material                | .....               |         | <b>Plastic waste</b>          |        |
| Water to steam (M <sub>1</sub> ) | .....               |         | Before test                   | .....g |
| Water to steam (M <sub>2</sub> ) | .....               |         | After test                    | .....g |
| <b>Temperature (°C)</b>          |                     |         | Dry pan only                  | .....g |
| Normal water                     | .....               |         | Charcoal + pan before test    | .....g |
| Boiling water                    | .....               |         | Charcoal + pan after test     | .....g |
| Water after test                 | .....               |         | Ash + pan                     | .....g |
| PG chamber (cold)                | .....               |         | Normal charcoal + pan         | .....g |
| At start of PG gas               | .....               |         | Dry charcoal + pan            | .....g |
| Steam generation                 | .....               |         |                               |        |
| Water starts boil                | .....               |         |                               |        |

### Table III-2: Time / temperature and mass variations during WBT

| Activity / changes in temperature | Temperature (°C) | Time (min) | Mass of pot + water | Activity/changes in mass |
|-----------------------------------|------------------|------------|---------------------|--------------------------|
| Normal cold water                 |                  |            |                     | At start                 |
| Fire starts                       |                  |            |                     | When boiling starts      |
| PG gas starts                     |                  |            |                     | Pot keeps on boiling     |
| Steam addition                    |                  |            |                     | Pot keeps on boiling     |
| Simmering/5mins                   |                  |            |                     | Pot keeps on boiling     |
| Simmering                         |                  |            |                     | Pot keeps on boiling     |
| Simmering                         |                  |            |                     | Pot keeps on boiling     |
| Simmering                         |                  |            |                     | Pot keeps on boiling     |
| End of test                       |                  |            |                     | End of test              |
| Remarks                           |                  |            |                     | Remarks                  |

**Table III-3: Results of water boiling tests (WBTs)**

| 1. High power test (cold start) | Units | Test 1 | Test 2 | Test 3 | Average | St dev |
|---------------------------------|-------|--------|--------|--------|---------|--------|
| Time to boil pot 1              | Min   |        |        |        |         |        |
| Burning rate                    | g/min |        |        |        |         |        |
| Thermal efficiency              | %     |        |        |        |         |        |
| Specific fuel consumption       | g     |        |        |        |         |        |

**Table III-4: Variables with values that are constant during each phase of the WBT**

| Variable (Unit)                                     | Symbol           | Value for the variable in experiments |    |     |    |   |      | Remarks |
|---|------------------|---------------------------------------|----|-----|----|---|------|---------|
|   |                  | I                                     | II | III | IV | V | Mean |         |
| Gross calorific value for charcoal (MJ/kg)          | HHV              |                                       |    |     |    |   |      |         |
| Calorific value for plastic waste (MJ/kg)           | HHV <sub>p</sub> |                                       |    |     |    |   |      |         |
| Charcoal moisture content (%-wet basis)             | m                |                                       |    |     |    |   |      |         |
| Effective calorific value of charcoal               | C <sub>eff</sub> |                                       |    |     |    |   |      |         |
| Dry weight of empty pot (grams)                     | P                |                                       |    |     |    |   |      |         |
| Weight of empty container for weighing char (grams) | K                |                                       |    |     |    |   |      |         |

**Table III-5: Directly measured variables**

| Variable  | Symbol   | Value for the variable in experiments |    |     |    |   |      | Remarks |
|---|----------|---------------------------------------|----|-----|----|---|------|---------|
|   |          | I                                     | II | III | IV | V | Mean |         |
| Weight of unused plastic waste until water boils (grams)    | $f_{si}$ |                                       |    |     |    |   |      |         |
| Weight of pot with water when the water first boils (grams) | $p_{si}$ |                                       |    |     |    |   |      |         |
| Water temperature at boiling point ( $T_s = T_b$ ) (°C)     | $T_{si}$ |                                       |    |     |    |   |      |         |
| Time at start of simmering (min)                            | $t_{si}$ |                                       |    |     |    |   |      |         |
| Weight of unburned charcoal after test (grams)              | $f_{sf}$ |                                       |    |     |    |   |      |         |
| Weight of charcoal after test (grams)                       | $c_s$    |                                       |    |     |    |   |      |         |
| Weight of char produced                                     |          |                                       |    |     |    |   |      |         |
| Weight of pot with water after test (grams)                 | $p_{sf}$ |                                       |    |     |    |   |      |         |
| Water temperature at end of test (°C)                       | $T_{sf}$ |                                       |    |     |    |   |      |         |
| Time at end of test (min)                                   | $t_{sf}$ |                                       |    |     |    |   |      |         |

**Table III-6: Results obtained from calculations**

| Calculated variables                 | Symbols      | Calculated values for variable in experiments |    |     |    |   |      | Inferences/remarks |
|--------------------------------------|--------------|---|----|-----|----|---|------|--------------------|
|                                      |              | I   | II | III | IV | V | mean |                    |
| Plastic consumed (g)                 | $f_{cm}$     |   |    |     |    |   |      |                    |
| Change in char during test phase (g) | $\Delta c_c$ |   |    |     |    |   |      |                    |
| Charcoal consumed (g)                | $f_{cd}$     |   |    |     |    |   |      |                    |
| Water vaporised (g)                  | $w_{cv}$     |   |    |     |    |   |      |                    |
| Water remaining at end of test (g)   | $w_{cr}$     |   |    |     |    |   |      |                    |
| Duration of phase (min)              | $\Delta t_c$ |   |    |     |    |   |      |                    |
| Thermal efficiency                   | $h_c$        |   |    |     |    |   |      |                    |

**Table III-7: Evaluation of previous exercise in preparation for the subsequent experiment**

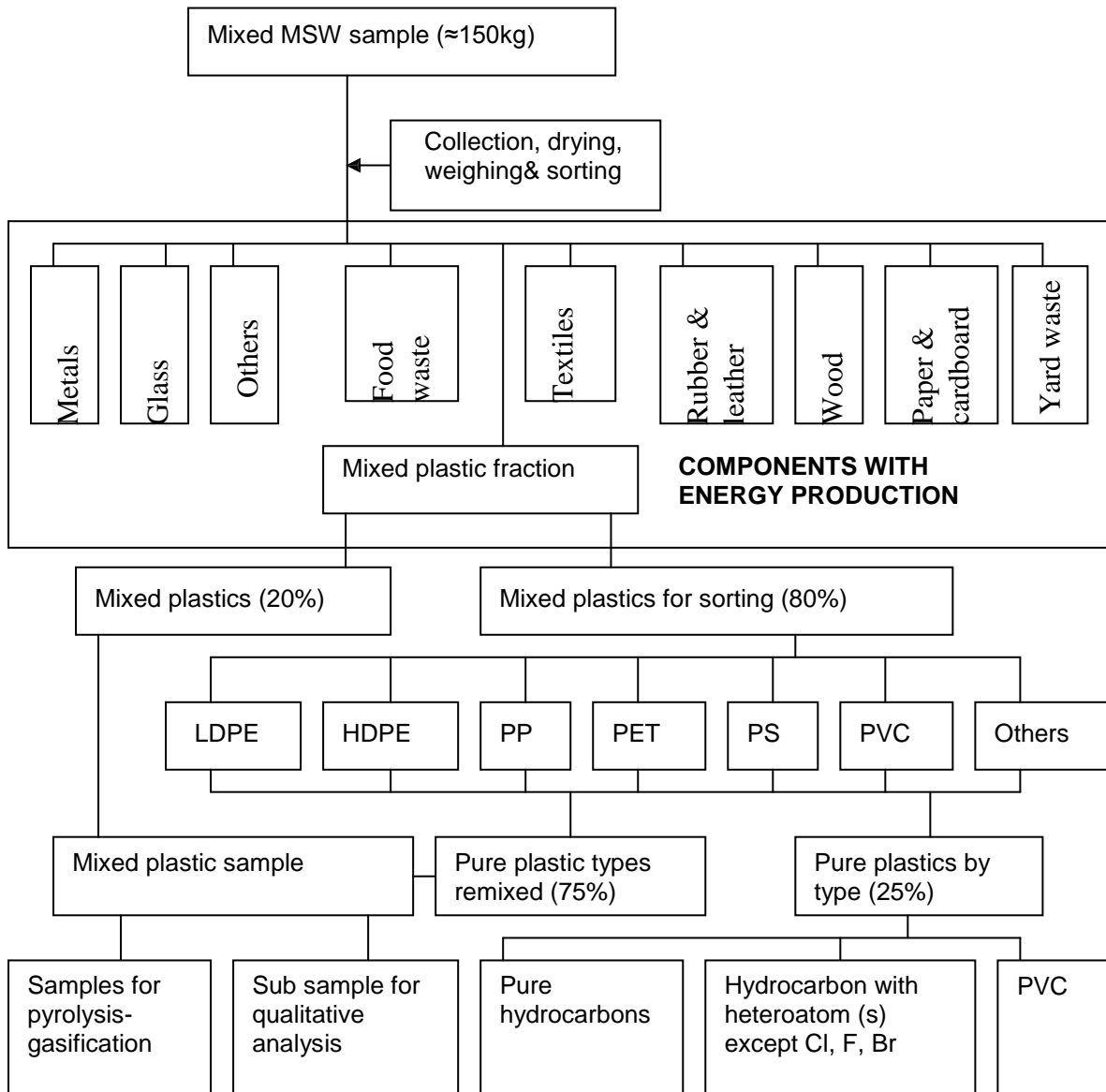
|                                |  |                           |  |
|--------------------------------|--|---------------------------|--|
| Expt. No.                      |  | Environmental constraints |  |
| Date                           |  |                           |  |
| Time                           |  |                           |  |
| Objectives                     |  |                           |  |
| Procedure                      |  |                           |  |
| Results                        |  |                           |  |
| Implication of results/figures |  |                           |  |
| Problems encountered           |  |                           |  |
| Proposed solutions             |  |                           |  |
| Recommendations                |  |                           |  |

## Appendix IV: Example of the experimental report for experiment no. 15

|                                |   |                           |  |
|--------------------------------|---|---------------------------|--|
| Expt. No. 15                   | Testing of stove, preparing feedstock and weighing of relevant components   | Environmental constraints |  |
| Date                           | 5 - 6. 10. 2009   |                           |  |
| Time                           | 8.00 - 18.00  |                           |  |
| Objectives                     | <ul style="list-style-type: none"> <li>- Evaluate the functioning of the PG stove with the insulation of the reactor chamber and gas conveying pipes</li> <li>- Use only burning charcoal to initiate the PG process noting the rate of PG chamber and water temperature variations</li> <li>- Observe the function of the screw-driven loader and impact of continuous feeding of plastic feedstock on stove performance (gas combustion, smoking, temperature variations etc)</li> </ul>  |                           |  |
| Procedure                      | <ul style="list-style-type: none"> <li>- After weighing the stove and relevant components, the stove is mounted. Weights of plastics, pot, and water including charcoal were determined.</li> <li>- Measurement of initial temperature of water, surroundings and PG chamber including volume water for steam formation</li> <li>- Only kerosene applied to charcoal was used to initiate the PG process</li> <li>- PG chamber temperature was allowed to increase up to over 200°C before plastic was driven in and steam addition was made when the pyrolysis gas liberation began</li> <li>- Temperature of water and PG chamber were recorded every 5minutes</li> </ul> |                           |  |
| Results                        | <ul style="list-style-type: none"> <li>- Process ran successfully with temperature of PG chamber and water increasing continuously</li> <li>- With addition of steam and continuous feeding of the plastic waste, the process continued over 90minutes</li> <li>- Flame was considerably better and little smoke production was observed</li> </ul>   |                           |  |
| Implication of results/figures | <ul style="list-style-type: none"> <li>- Temperature of PG chamber increased relatively slowly but became more rapid with production of PG gas production and combustion</li> <li>- PG chamber rose rapidly to 545°C while that of water in the pot rose gradually but ending at 78°C</li> <li>- PG chamber temperature was more stable due to insulation but began to fluctuate with the combustion of the insulation material behind the reactor</li> </ul>   |                           |  |
| Problems encountered           | <ul style="list-style-type: none"> <li>- Flame was generally carried by air currents to behind the reactor toward the exhaust gas outlet. This resulted in high heating and burning of the glass wool on the PG chamber and external casing around the exhaust gas outlet which became red hot</li> <li>- Surface of the stove casing curved outwards resulting in a point contact between bottom of the pot</li> <li>- Flame burning away from the bottom of the PG chamber and burning of the insulation lead to heat loses leading to the termination of the PG gas production</li> </ul>  |                           |  |

|                                    |  |
|------------------------------------|--|
|                                    | <ul style="list-style-type: none"> <li>- The continuous feeding of the plastic feedstock was successful but requires a more discharge and recharge consistency</li> </ul>  |
| Proposed solutions                 | <ul style="list-style-type: none"> <li>- A design and construction of an air inlet control is required to prevent direct air flow on the flame</li> <li>- Insulation material used needs to be changed to get material with higher temperature resistance</li> <li>- Surface of stove casing needs to be improved to achieve maximum surface area contact between stove and pot by constructing a new top plate with stronger metal</li> <li>- Continuous feeding of plastic in small quantities should be followed by regular recharge to prevent long time recharge with inconsistent PG gas production</li> </ul> |
| Recommendations & remarks          | <ul style="list-style-type: none"> <li>- This exercise was most successful with PG chamber temperature stabilized and consistently rising including that of water</li> <li>- Solving the above proposed problem by applying the proposed solutions would enhance the process and improve stove functioning</li> </ul>  |
| Objectives for the next experiment | <ul style="list-style-type: none"> <li>- After carrying out the above suggested optimisation strategies other exhaust gas samples would be collection at various stages of the combustion process for analysis (before PG gas production commences, during PG gas production and burning, during shooting down with cooling)</li> </ul>  |

## Appendix V: Procedure for waste and plastic waste analysis





**Table V-1: Forms for recording masses and percentages of major waste fractions in MSW**

|                   | Waste fraction  | Food waste | Yard waste | Paper & paperboards | Mixed plastics | Rubber & leather | Textiles | wood | Glass | Metals | Others |
|-------------------|-----------------|------------|------------|---------------------|----------------|------------------|----------|------|-------|--------|--------|
| Germany (Cottbus) | Mass /g         |            |            |                     |                |                  |          |      |       |        |        |
|                   | Mass percentage |            |            |                     |                |                  |          |      |       |        |        |
| Nigeria (Lagos)   | Mass /g         |            |            |                     |                |                  |          |      |       |        |        |
|                   | Mass percentage |            |            |                     |                |                  |          |      |       |        |        |
|                   |                 |            |            |                     |                |                  |          |      |       |        |        |

**Table V-2: Mass and percentage of major plastic waste components in MSW**

|                    | Plastic type | LDPE & LLDPE | HDPE | PP | PET | PS | PVC | PC | PBT | PU | Others |
|--------------------|--------------|--------------|------|----|-----|----|-----|----|-----|----|--------|
| Germany            | Mass /g      |              |      |    |     |    |     |    |     |    |        |
|                    | % by Mass    |              |      |    |     |    |     |    |     |    |        |
| Cameroon (Bamenda) | Mass /g      |              |      |    |     |    |     |    |     |    |        |
|                    | % by Mass    |              |      |    |     |    |     |    |     |    |        |

**Table V-3: Mixed MSW analysis data for Cottbus, Germany**

| Mixed Municipal solid waste (MSW) sample analysis in Cottbus, Germany   |  |                             |                        |                        |                         |   |  |        |                   |   |       |  |  |
|---|--|-----------------------------|------------------------|------------------------|-------------------------|---|--|--------|-------------------|---|-------|--|--|
| Items   | MSW sample + bin   | Bin                         | MSW sample             | Water lost after 7days | Dried waste after 7days |   | Remarks: drying was indoors in winter                    |        |                   |   |       |  |  |
| Quantity/kg   | 224.8  | 62.7                        | 162.1                  | 23.9 (14.7%)           | 138.3 (85.3)            |   |  |        |                   |   |       |  |  |
| Waste fraction  | Food waste   | Residue waste               | Paper & cardboards     | wood                   | Textiles & Napkins      | Mixed plastics                              | WEEE   | Glass  | Metals            | Others  | water | High waste /water content requiring drying |  |
| Mass/kg   | 13.90  | 32.00                       | 27.30                  | 0.28                   | 20.22                   | 24.60                                       | 2.10   | 13.20  | 4.60              | 0.07  | 23.80 |  |  |
| Mass /%   | 8.57   | 19.74                       | 16.84                  | 0.17                   | 12.48                   | 15.18                                       | 1.30   | 8.14   | 2.84              | 0.04  | 14.70 |  |  |
| Usable waste fraction/%   | 10.06  | 23.15                       | 19.75                  | 0.02                   | 14.63                   | 17.80                                       | 1.52   | 9.55   | 3.33              | Eliminated  |       |  |  |
| Material & energy resources recovery potential mass %   | Biogas or/and composting: 33.21%   |                             |                        |                        |                         |   | Reusable or recyclable to secondary raw materials: 14.40 |        | Land filled: 0.19 | <ul style="list-style-type: none"> <li>• 99.81% of waste has energy &amp; secondary material recovery</li> <li>• An almost zero waste scenario with only 0.19% to land field is achievable</li> </ul> |       |  |  |
|   | Biodegradable to manure (aerobic): 52.98%  |                             |                        |                        |                         |   |  |        |                   |   |       |  |  |
|   | High calorific value waste fraction PGT: 85.41%  |                             |                        |                        |                         |   |  |        |                   |   |       |  |  |
|   | Waste fraction is combustible after drying   |                             |                        |                        |                         |   | Non-combustible  |        |                   |   |       |  |  |
| Mixed plastic waste fraction analysis   |  |                             |                        |                        |                         |   |  |        |                   |   |       |  |  |
| Items   | Mass of plastic waste fraction   | Mass after 1 week drying/kg | Weight % lost of water | Dried plastic waste    | Waste to landfill       | Final weight of plastic waste characterized |  |        |                   |   |       |  |  |
| Quantity/kg   | 24.6   | 2.00                        | 8.13                   | 22.6                   | 0.20                    | 22.40                                       |  |        |                   |   |       |  |  |
| Plastic type /code  | PET: 1   | HDPE: 2                     | PVC:                   | LDPE: 4                | PP: 5                   | PS: 6                                       | Others: 7  | Total  | Lost              | <ul style="list-style-type: none"> <li>• Identifying plastic component needs integration of various methods</li> <li>• PVC is not common in plastic packaging</li> </ul>                              |       |  |  |
| Mass of identifiable plastic types/kg   | 0.26   | 1.09                        | 0                      | 0.30                   | 3.50                    | 0.35  | 16.90  | 22.40  | ---               |   |       |  |  |
| Percentage of identifiable plastic/%  | 1.16   | 4.80                        | 0                      | 1.31                   | 15.49                   | 1.57  | 74.78  | 99.11  | 0.89              |   |       |  |  |
| Percentage of usable identified plastics/%  | 1.17   | 4.84                        | 0                      | 1.32                   | 15.63                   | 1.58  | 75.46  | 100.00 | ---               |   |       |  |  |
| Identification of unlabelled plastics   | IR-spectroscopic identified 4 components made from PVC (tablet package, video cassettes, baby feeding bottles & drip set pipe) |                             |                        |                        |                         |   |  |        |                   |   |       |  |  |
| Others: PC, PBT, PU, polyester, poly vinyl acetate, alkyl resins, polyamide, ABS, acryl nitrile (AS), silicone) |  |                             |                        |                        |                         |   |  |        |                   |   |       |  |  |

## Appendix VI: Checklist for pollution and emission impact analysis

| Checklist for pollution impact analysis |                                     |                           |                           |
|---|-------------------------------------|---------------------------|---------------------------|
| Components                              | Presence in pyrolysis-synthesis gas | Presence in Exhaust gases | Presence in solid residue |
| Carbon monoxide (CO)                    |                                     |                           |                           |
| Hydrogen (H <sub>2</sub> )              |                                     |                           |                           |
| Carbon dioxide (CO <sub>2</sub> )       |                                     |                           |                           |
| Methane (CH <sub>4</sub> )              |                                     |                           |                           |
| Water vapour (H <sub>2</sub> O(g))      |                                     |                           |                           |
| Other hydrocarbons (VOCs)               |                                     |                           |                           |
| Unburned carbon (soot)                  |                                     |                           |                           |
| Common heavy metals: Cadmium (Cd)       |                                     |                           |                           |
| Lead (Pb)                               |                                     |                           |                           |
| Mercury (Hg)                            |                                     |                           |                           |
| Halogens                                |                                     |                           |                           |

## Appendix VII: Pictures of waste treatment, disposal and impacts

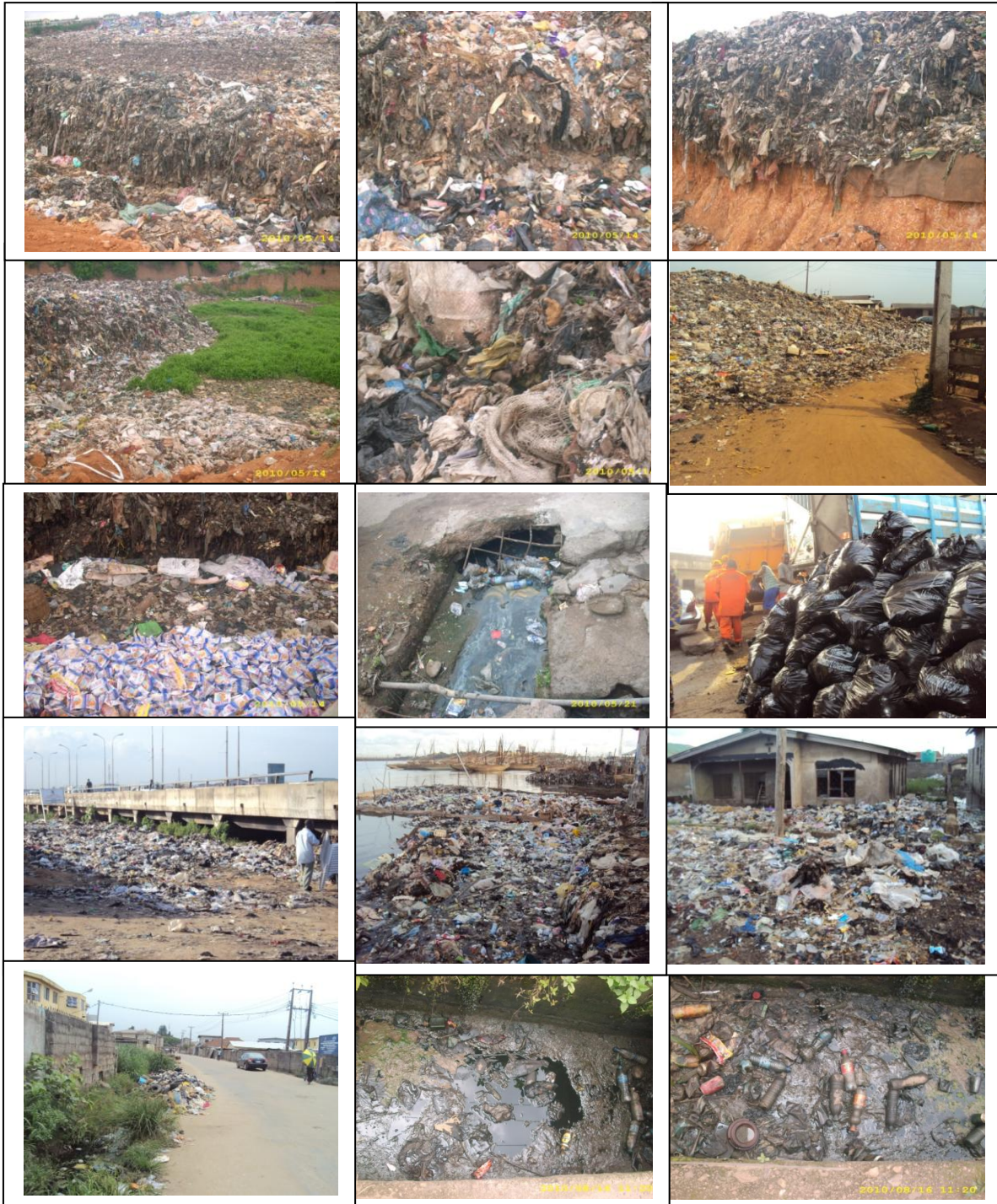


A: Hygiene and sanitation based on waste collection, storage and disposal



B: Ash storage and disposal





C: Dominance of plastic waste in landfills and impacts on the environment

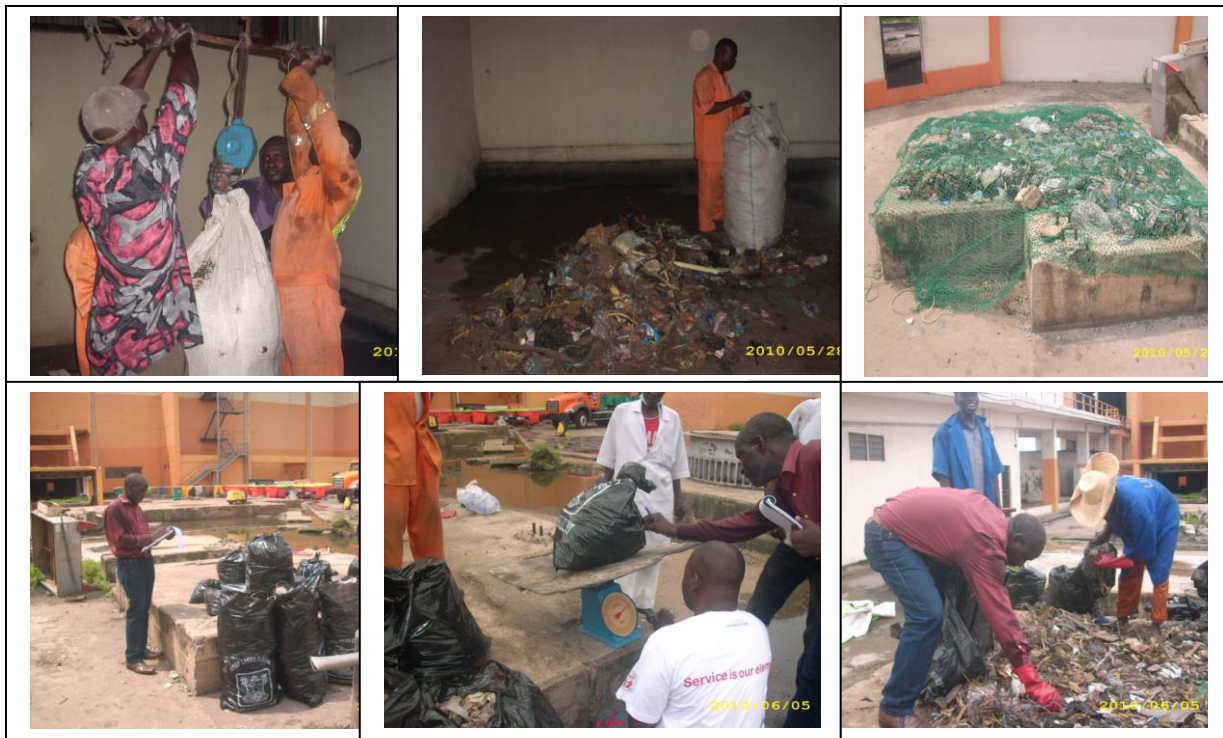




D: Basic tools used in developing and optimizing the PG technology



E: Waste pretreatment for plastic recovery



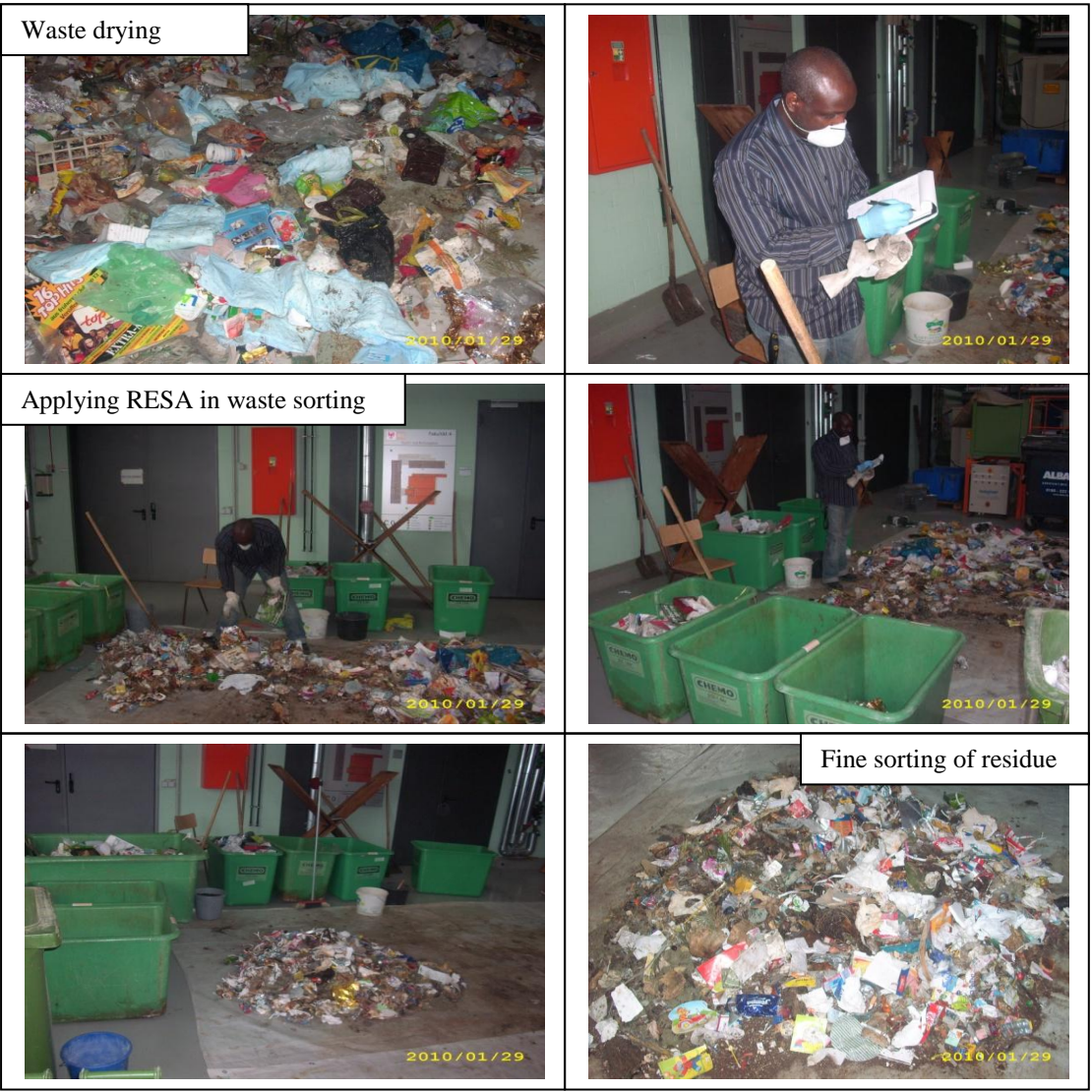
F: RESA waste analysis processes at STLS





G: Composting and use of bio-fertilizer to improved agric yield





H: Application of RESA in sorting commingled waste at BTU Cottbus



I: Waste drying before sorting to remove moisture





J: Applying of the RESA method using informed waste sorters



K: Major waste fractions sorted with over 95% efficiency using RESA





L: Sorting of fine waste of 90-100% biodegradable organic components



M: Application of RESA in recovering recyclable materials



N: Representative waste sample characterisations





O: Plastic waste fraction pretreatment and sorting



P: Plastic waste identification using sink-float test





Q: Plastic waste identification using near IR spectroscopy



R: Sample of non-PVC hydrocarbons plastics sorted from plastic fraction



S: Flame chases the gas ensuring all VOCs are completely burned





U: Various flame situations



T: Pretreatment and use of plastics for energy recovery





V: Production of biogas from biodegradable waste fraction



W: Construction of PG technology using 60-80% scrap metals





X: Use of scrap metals to make agric processing machinery