Climate change mitigation technologies in the Gambian energy, transport and waste sectors

Author
Momodou Njie, PhD

January 2017

Table of Contents

Acknowledgements

List of abbreviations and acronyms

atm	atmosphere
BPEV	Battery powered electric vehicle
BTU	British Thermal Unit
cc	cubic centimetres
COP	Conference f the Parties to the UNFCCC
DWR	Department of Water Resources
EUR	Euro
FCEV	Fuel cell electric vehicle
GBA	Greater Banjul Area
GHG(s)	Greenhouse gas(es)
GEF	The Global Environment Facility
GOTG	Government of the Gambia
GTTI	Gambia Technical Training Institute
hp	horsepower
INDC	Intended Nationally Determined Contributions
IPP(s)	Independent Power Producer(s)
ISIC	International Standard Industrial Classification
JPY	Japanese Yen
Km	Kilometer
KPa	KiloPascal
LECRDS	Low Emissions Climate Resilient Development Strategies
LGA	Local Government Authority
mb	millibar
MCA	Multi-criteria Analysis
MoECCWWF	Ministry of Environment, Climate Change, Wildlife, Water &Fisheries
MOHSW	Ministry of Health and Social Welfare
MoPE	Ministry of Petroleum and Energy
MOWCI	Ministry of Works, Transport and Infrastructure
MSW	Municipal Solid Waste
MW	MegaWatt
NAMAs	Nationally Appropriate Mitigation Actions
NAWEC	National Water and Electricity Company
NCC	National Climate Committee
NEA	National Environment Agency
NRA	National Roads Authority
NCCP	National Climate Change Policy
PAGE	Programme[1] for accelerated growth and employment
psi	pounds per square inch
PURA	Public Regulatory Authority
rad	radian
rpm	revolutions per minute
SNC	Second National Communication
TAP	Technology Action Plan
TNA	Technology Needs Assessment
TtW	Tank-to-Wheels
UNFCCC	United Nations Convention on Climate Change
UNEP	United Nations Environment Programme

---

[1] extended to a fifth year following, MTE (in 2014) and pending finalisation of successor programme

USD	US Dollar
V	Volt
W	Watt
WtE	Waste-to-Energy
WtW	Well-to-Wheels

Physical units

1Gg = 1,000,000,000 g
1Gg= 1,000 metric tonnes (mt)
1 ha = 1ha10,000 m^2
1ha= 0.01 Km^2
1kV = 1,000V
1kW= 1,000 W
1MW = 1,000 W
1GW=1,000 MW

1 US gallon = 3785.41 cc
1 Imperial gallon = 4546.09 cc
1 litre = 1,000 cc
1 mile = 1.60934 Km
1 rad.s^{-1} = 0.5493 rpm
1 hp = 754.7 W
1 BTU = 1055.06 J
1 bar = 14.5038 psi
1 bar = 100 KPa
1 atm = 101.3 KPa
1 atm = 1013 mb

Executive Summary

This study, conducted within the ambit of the GEF (Global Environment Facility) funded Technology Needs Assessment (TNA) project, fulfills specific objectives of the Poznan Strategic Programme whilst simultaneously strengthening national capacity in participative methodologies and multi-criteria decision-making techniques.

As recently as 2015, the Gambia did not have a policy specifically addressing climate change mitigation or adaptation. Viewed from new perspectives however, some existing policies and policy measures, notably energy sector polices, hold significant promise for impactful abatement of greenhouse gas emissions. Immediately, what the current TNA does is to bring significant value-addition to the Gambia's National Communications, mandatory under Article 4.5 of United Nations Convention on Climate Change (UNFCCC). Crucially, the TNA project is expected to culminate in the development of a national Technology Action Plan (TAP) that addresses *inter alia* policy, finance and cultural-related barriers to the uptake and scaling up of investment in low-carbon and climate resilient technologies, with the support of a United Nations Environment Programme (UNEP) consortium of experts. A first step on that path however constitutes the identification and prioritisation of technologies most appropriate for curtailing greenhouse gas (GHG) emissions in selected sectors designated in the Gambia's intended nationally determined contributions (INDC) to global GHG mitigation efforts.

In light of the task at hand, a participatory problem solving approach facilitated by the author who not only got stakeholders actively involved in situational analyses, identification of generic mitigation options, and technological options cross-validation in open meetings and working group sessions; but capacitated stakeholders to carry out prioritisation of technology options/alternatives through hands-on training on multi-criteria analysis (MCA). Criteria used in all technology prioritisation exercises invariably reflect environmental, social and economic pre-requisites for and/or corresponding impacts of technology deployment, as well as technical attributes mirroring performance of proposed technologies.

Based on their relevance to the development and implementation of low emissions climate resilient development strategies (LECRDS) and recently promulgated INDC, three key economic (sub)sectors, namely, energy, transport, and waste, were studied in this report and the findings summarised as follows:

Energy

The Gambia has parallel energy markets in traditional and modern energy fuels and carriers. The latter, with a market share of approximately 40%, is built around product supply and demand dynamics and price adjustments in petroleum and electricity subsectors. About 60% of fuel imported is used by the National Water and Electricity Company (NAWEC) is used for power generation in utility-scale generators to produce around 250GWh of electricity annually that is distributed to 46% of homes. Exceptionally, two small independent power producers using small-scale wind turbines with aggregate capacity of 250kW, provide surplus power to NAWEC at feed-in tariffs established under the Electricity Act. Carbon monoxide (CO) and carbon dioxide (CO_2) emissions from power generation in 2012, converted to carbon dioxide equivalent units (CO_2-eq), are estimated to be between 265 and 400 GgCO_2-eq, representing an annual growth rate of 10 to 14% between

2000 and 2012. To reduce these emissions in alignment with the Gambia's INDC, the TNA proposed upscaling/introduction of solar photovoltaic (PV) and wind technologies, or deployment of tidal stream or combined cycle diesel generators, the last two virtually absent from the landscape of the Gambian electricity sub-sector.

Considering various factors within an MCA framework, stakeholders prioritised combined cycle diesel generators and wind turbines as the top two technologies of choice. It is sufficient to state that power plants based on the operation of technologies that use non-fossil energy resources such as wind have GHG abatement potentials equivalent to emissions generated from a conventional fossil fuel-fired generator of equal power rating. After adjustment for capacity factors a 6MW wind turbine facility is expected to deliver 4.6GgCO_2/year in emissions reductions. Whereas a combined cycle diesel generation plant reduces fuel and correlated emissions by 6%, it has the advantage of more reliable power generation, compared to renewable technologies that are based on intermittent energy resources.

Transport

Whilst the TNA acknowledges the significance and briefly describes the water and air transportation modes, it focuses on vehicular road transport due to scale issues, growth dynamics and contributions to GHG emissions.

The number of passenger- and freight-carrying vehicles of all categories plying Gambian roads is estimated to be around 70,000. According to transport sector operators, more than 60% of road vehicles use internal combustion engines fitted with spark ignition technology. A key feature of the transport sector is the high level of private and distributed ownership of freight and passenger vehicles. In the densely populated metropolitan area of Kanifing, a sizeable and increasing population of bicycles, and to a lesser extent mopeds, provide additional personal mobility for some people living considerable distances from routes normally served by public transport and taxis.

The combination of high vehicle numbers and limited road capacity, compounded by poor traffic management, contributes to congestion along main road arteries within the Greater Banjul Area (GBA), increases travel times, and results in higher fuel consumption and CO_2 emissions, with unquantified economic and health impacts on road users and local communities.

According to a historic reconstruction of GHG emissions in the transport sector, carbon dioxide (CO_2) emissions grew by 8.8% per annum between 2000 and 2012, compared to 1.2% in carbon monoxide (CO) emissions over the same period. Two broad technological categories, namely, fuel-saving and electric powertrain technologies, are presented as potential technologies for mitigating vehicular emissions. From the set of technology options comprising direct fuel injection, turbocharger, battery-powered electric vehicle (BPEV) and fuel cell electric vehicles (FCEV), stakeholders ranked direct fuel injection and turbocharger as the top two technologies using MCA. On a vehicular basis, fuel-saving technologies identified are expected to deliver a 10-15% reduction in GHG emissions. In contrast, small and light duty electric vehicles such as battery-powered electric vehicles (BPEVs) and fuel cell electric vehicles (FCEVs), depending on their source of electricity, could deliver up to 40% emissions reduction compared to an ordinary diesel-powered car engine. However, direct and accompanying infrastructure costs appear to be the biggest handicap of electric powertrain vehicles at the moment.

Waste

Aligned with the Gambia's INDC, the current TNA report focuses on problems related to the control of GHGs from municipal solid waste (MSW). For pragmatic reasons, the study is restricted to the Greater Banjul Area, where management challenges linked to MSW have reached epic proportions.

Waste disposal facilities, implicitly owned and operated by local government authorities (LGAs), currently function as open/primitive dumpsites. According to a decade-old study, MSW is composed of 49% biodegradable and 51% non-biodegradable matter by weight. The overwhelming bulk of MSW is allowed to build up and decay without any form of treatment. MSW placed in dumps is sometimes burnt in open air and occasionally compacted to extend the dumpsite's service life. Upstream and on-site waste recycling by small entrepreneurs and scavengers, respectively, occurs on a small scale. Owing partly to the lack of data and comprehensive studies, there is considerable difficulty in establishing trends and annual rates of GHG emissions from primitive dumpsites. Still, this study finds a 1.4% annual growth of methane (CH_4) emissions from the Bakoteh (in Kanifing Municipality) and Mile 2 (in Banjul), the two official dumpsites in the GBA.

As MSW generation continues to rise concomitantly with population growth in the GBA, the TNA report proposed landfill technologies, anaerobic digesters, incinerators and static aerated pile composting as means of curbing fugitive methane emissions from large primitive dumpsites. Technology prioritisation using an MCA decision-support tool concluded by confirming bioreactor and sanitary landfill as the two highest ranked technologies under most conditions, while composting is a top-two contender under certain conditions. Bioreactor landfills, a more sophisticated form of sanitary landfill design, have added advantages of speeding up methane production and thus shortening landfill stabilisation timescales. Depending therefore on the efficiency of leakage control measures and methane capture subsystems, landfill technology is capable of reducing uncontrolled methane emissions from waste disposal sites with a greater or lesser degree of success. On the other hand, the diversion of compostable material from landfill to composting operations, as a way of avoiding CH_4 emissions, could potentially reduce GHG emission by about 83%.

Energy, Transport and Waste

At first glance, some of the results that surfaced from the technology prioritisation exercises appear counter-intuitive, notably the strong performance of the combined cycle diesel generators (energy sector) and bioreactor landfill (waste sector), vis-à-vis other technologies that stakeholders are more familiar with. Still, it is important to note that current rankings should not stop decision-makers from including utility-scale solar PV and aerated static pile composting technologies in further technology assessments, or strategic deployment of specific technologies on different (management) scales. Although not materially affecting the final results of the MCA, the case for bridging/reducing knowledge gaps and uncertainties in GHG emissions is a compelling one that requires urgent attention. Furthermore, the current assessment conclude that positive impacts of technology on sectoral

GHG mitigation could be significantly augmented through climate change education, policy reforms, public procurement and investments, economic incentives, and, if need be, the creation of specialised organisation responsible for handling emergent or recalcitrant challenges in some sectors.

Chapter 1 Introduction

1. 1 About the TNA project

Since 2009, a global Technology Needs Assessment (TNA) Project, under the Poznan Strategic Programme on Technology Transfer, financially supported by the Global Environment Facility (GEF) has availed developing country Parties to the United Nations Convention on Climate Change (UNFCCC) with financial and technical support to determine their technology priorities for the mitigation of greenhouse gas emissions and adaptation to climate change. Under the current phase of the TNA Project (i.e., Phase II), the Gambia is one of 25 countries implementing a TNA project built upon country-driven activities leading to identification, prioritisation and diffusion of climate-friendly and climate-smart technologies, with capacity building support and guidance from UDP[2] experts.

It is worth noting that the Gambia has previously **c**arried out and reported on its technology needs in previous national communications mandated under Article 4.5 of UNFCCC (GOTG, 2003; GOTG. 2012). Consequently, what the current TNA does is bring significant value-addition to the previous assessments. Crucially, the TNA project is expected to culminate in the development of a national Technology Action Plan (TAP) that addresses *inter alia* policy, finance and cultural-related barriers to the uptake and scaling up of investment in low-carbon and climate resilient technologies.

1.2 Existing national policies on climate change mitigation and development priorities

As a signatory to the UNFCCC and its related protocols, The Gambia has been actively involved in international negotiations to chart a sustainable greenhouse emissions pathway that keeps humanity safe from dangerous climate change. Until recently however, policies and response measures to mitigate and adapt to climate change have not been codified into an overarching policy that promotes a holistic view of diverse climate-sensitive activities and integrated solutions to overt risks and challenges. A National Climate Change Policy (NCCP) prepared under aegis of the GCCA[3] Support Project to the Gambia for ICZM and Mainstreaming climate Change (GC3SP), finalised in January 2016, represents the country’s determined and systematic response to individual climate threats and their positive feedbacks to sustainable development, wellbeing and ecological integrity.

The goal of the NCCP is to achieve the mainstreaming of climate change into national planning, budgeting, decision-making, and programme implementation, through effective institutional mechanisms, coordinated financial resources, and enhanced human resources capacity, by 2025. One of the focal issues addressed in the NCCP is the rapid transformation of the current economic structure and operations in sync with a low carbon and resilient economy. In this regard, specific objectives that give added impetus to the TNA include purposeful plans for deployment of sound and equitable adaptation and mitigation measures to reduce vulnerability to climate change and enable transition to a low-carbon economy. Activities identified and assigned emission reduction targets specified in the INDC fall within

---

[2] UNEP DTU Partnership that brings together experts from UNEP DTIE (formerly UNEP Risø Centre) Danish Technical University (DTU) and Energy Research Centre, ERC (university of Cape Town, South Africa)

[3] Global Climate Change Alliance

the agriculture, energy, manufacturing, transport, waste, and household sectors. At the same time, the INDC buttresses the point that technology transfer (Metz et al., 2001) has a critical role in the global community's successful response to climate change challenges, and articulate in detail specific technology transfer requirements in the afore-mentioned sectors.

National development priorities are set out in the government's four-year programme[4] for accelerated growth and employment- PAGE (GOTG, 2011). The latter's social and economic development objectives are underpinned by five strategic pillars as follows: 1) accelerating and sustaining economic growth; 2) improving and modernising infrastructure; 3) strengthening human capital; 4) improving governance and fighting corruption; and 5) reinforcing social cohesion. Alongside information and communication technology (ICT), energy and transport sectors crucially form the trio of infrastructure sectors targeted for modernisation. Climate change is included within the PAGE as a crosscutting issue, together with environment, disaster risk reduction and gender equality. A mid-term evaluation of the PAGE (Foon, 2014) found important inadequacies in its design and implementation, in particular the absence of a robust monitoring and evaluation (M&E) system, an underperforming coordinating mechanism, and sub-optimal resource mobilisation results. In the review, Foon (2014) reports completion of flagship road construction projects, significant achievements in the number of households with access to electricity, and grid electricity loss reduction. However, the contribution of renewable energy to grid-supplied electricity remained marginal and off target. On climate change, Foon (2014) reports inconsistent GHG emission data but offers no specific recommendations. It can be concluded therefore that successful implementation of sustainable development programmes was always going to be difficult in the absence of a climate policy and a properly resourced institutional structure to implement that policy.

1.3 Sector selection

Selection of TNA mitigation sectors was an administrative decision consistent with national efforts to chart a trajectory for green development and strengthen the Gambia's image of a responsible global citizen. In fact, the energy sector especially the electricity generation sub-sector, transport and waste sectors feature consistently among the top four sources of carbon dioxide (CO_2) and methane (CH_4) emissions in the Gambia's Second National Communication, SNC (GOTG, 2012a). This reality is acknowledged in both long-term strategic planning documents (Lamour, 2013), globally-oriented climate responses (GOTG, 2015)[5] and priority mitigation actions articulated in the form of nationally appropriate mitigation actions, NAMAs (Blodgett et al. 2015).

Following on NAMA project concepts built around solar photovoltaic (PV), wind turbine and landfill technologies, for the energy and waste sectors respectively (GOTG, 2012b), the commissioned study on low-emission climate-resilient development strategies, LECRDS (Lamour, 2013), validates *inter alia* 1) clean energy production and higher electricity transport efficiency; 2) composting, incineration and digestion

---

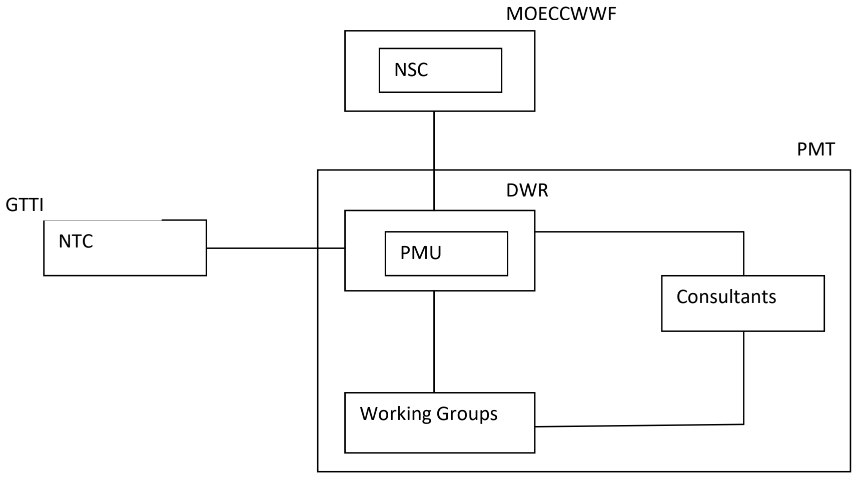
[4] extended to a fifth year following, MTE (in 2014) and pending finalisation of successor programme

[5] The INDCs are to take effect from 2020 and will detail actions the parties will take to address climate change.

techniques/technologies to tackle climate problems linked to solid waste management; and 3) mass transport systems and catalytic converters for the transport sector. Crucially, the Gambia's intended nationally determined contributions, INDC (GOTG, 2015), re-affirms energy, transport and waste sectors as focal areas assigned specific mitigation targets. In short, working with the same sectors follows a logic of continuity and value-addition that strengthens gains already made towards achieving national goals for a sustainable future.

Chapter 2 Institutional arrangement for the TNA and the stakeholder involvement

The relevant institutional structure for implementing the TNA in the Gambia is shown in Figure 2.1 below.



LEGEND
MOECCWWF = Ministry of Environment, Climate Change, Wildlife Water and Fisheries
NSC = National Steering Committee
GTTI = Gambia Technical Training Institute
NTC = National Technology Centre
DWR = Department of Water Resources
PMU = Project Management Unit
PMT = Project Management Team

Figure 2.1 *TNA project organisational structure*

Project governance is centred in the National Steering Committee (NSC), constituted by gender, development, environmental, business and management, energy, finance, and climate specialists and policy analysts and specialists. The NSC whose remit is to manage the strategic direction of the TNA project is headed by one of two deputy permanent secretaries at the Ministry of Environment, Climate Change, Wildlife, Water and Fisheries (MoECCWWF), the leading public institution for climate change administration and policy-making.

At the operational level, a Project Management Unit (PMU), constituted by the Project Director, Project Coordinator and Accountant, handles project accounts and provides administrative and logistic support to working groups and the author. The PMU is hosted by Department of Water Resources (DWR) and headed by its Director. It is also worth noting that the Project Coordinator is from the Gambia Technical Training Institute (GTTI), the Focal Point for technology transfer in The Gambia. Under the Bali Action Plan, GTTI has been designated as the Gambia’s National Technology Centre, and its Director-General is a key member of the NSC of the TNA project. The Gambia’s UNFCCC Focal Point who also sits on the NSC is from the Department of Water Resources (DWR), one of several subsidiary agencies of MoECCWWF.

The Project Management Team (PMT) which comprises non-executive project members is discussed in the next section.

2.1 National TNA team

The Project Management Team (PMT), illustrated as an integral part of the TNA project structure in figure 2.1, is the institutional equivalent of the National TNA Team. The PMT assembles technical members of the PMU, TNA sectoral working group members and the author, and is entrusted with carrying out scheduled TNA activities. While PMT members carry out individual tasks on their own separately, members converged in groups to work on collective tasks including joint decision-making. In these sessions, prior distributed meeting agendas set the tone of consultations. Between meetings, members communicate on relevant topics/issues by voice, SMS text and email. Both TNA Project Director and Coordinator report on implementation progress to the NSC. In principle, working group members are drawn from the National Climate Change Committee; a broad multi-stakeholder forum on climate change policy discussions.

2.2 Stakeholder Engagement Process followed in the TNA

In addition to representatives of institutions involved in the governance of the TNA project, proactive stakeholders are drawn from the public, private and voluntary sectors, represented in the National Climate Change Committee (NCCC). At the outset, all major stakeholder institutions/organisations were invited to an inception workshop which provided background information on the project; its history, objectives and institutional arrangements. The inception/inaugural workshop was graced by the presence of Honourable Minister responsible for Environment, Climate Change, Wildlife, Water and Fisheries, who launched the TNA project, re-affirming the political endorsement of his ministry, and the Gambian government in general.

Stakeholder engagement in general had two broad objectives: 1) to seek views and opinions of stakeholders on matters; and 2) to make transparent decisions jointly. The first was pursued through consultative workshops, and the second through working sessions held between the author and working group members.[6] Considering that thematic working groups on transport and waste management do not currently exist under the NCC's Mitigation Cluster, and further considering the intersectoral dimensions of both sectors, a mixed group of stakeholders including lead departments was established to work closely with the author and to take collective ownership of the decision-making process. In all cases, prior distributed meeting agendas served as the basis for stakeholder engagement. Unfortunately, Ministry of Health, Banjul City Council, Kanifing Municipal Council, Gambia Police Force and Department of Community Development representatives were unable to participate in the process although they are key stakeholders. Other institutions that are part of the NCC Energy Task Force, which played a minor role in the process include the Gambia Bureau of Statistics (GBoS), Gambia Ports Authority (GPA), Gambia Renewable Energy Agency,

---

[6] Stakeholder participation was solicited through written communications from the project Director's Office. Keeping 4-day working week in mind, dates, venues and platforms for stakeholder engagement were established through wide consultation. For larger group meetings, venues were centrally located and readily accessible to participants. Smaller groups/face-to-face discussions also held in individual offices to ensure successful pursuit of stakeholder engagement objectives.

Moukhthara Holdings, Manufacturers Association and National Disaster Management Agency (NDMA).

Consultative workshops were organised to enable discovery of restricted sets of mitigation technology options. Using the carousel method,[7] participants who self-identify as a core group of committed stakeholders, identified, reviewed and validated structured and refined proposals put forward or emerging from the discussions, considered recommendations by the author, and carried out guided prioritisation of technologies, pursuant to an introduction to MCA methodology and worked examples.

2.3 Process for technology prioritisation

Technology prioritisation is part of the broader problem of technology deployment which is strongly correlated with private/public investment choices and technology transfer mechanisms anchored in global policies on sustainable development. In this study, proiritisation is carried out in four sequential decision-making steps, as follows:

1) Problem definition
2) Identification of alternatives
3) Articulation of criteria
4) Evaluation of alternatives

in which the first three steps amount to structuring the decision-making problem, and the fourth to its final analytical step (Anderson et al. 1991)

The process begins with building an understanding of relationship between key issues in each sector and existing technologies. To this end, a situation analysis covering the policy, organisational and technological landscapes in each of the selected sectors, and change drivers paved the way for identification of the most pressing challenges, some of which are solvable through strategic deployment of technologies that have a primary focus on stabilising and reversing current GHG emission trajectories, but are also capable of spurring economic growth and enhancing citizens' quality of life. Second, climate-friendly technologies with significant mitigation potential are identified through information canvassing by means of literature reviews and stakeholder consultations. For the type of quantitative analysis envisaged, a minimum of four alternative technologies per sector is emphasised for credibility of results arising from the TNA. It is worth noting that alternatives considered have similar objectives and time frames for meaningful comparison (BGS, 2006). Third, criteria facilitating comparison of alternative technologies are identified iteratively in consultative working group sessions to distill coherent criteria sets (Roy, 1985). Criteria

---

[7] The carousel method is a cooperative learning activity that affords participants the opportunity, on a rotational basis, to share ideas, introduce new information on a particular topic, review and discuss existing information, in order to boost group learning outcomes.

In practice, discovery takes place in four steps: *brainstorming* on the topic at hand, *filtering* (separating technical from non technical solutions), *pre-selection of technologies* (elaboration and amalgamation of similar concepts and correlation with specific technologies), and *cross-validation of technologies* identified. All steps follow the carousel method to ensure the process remains multi-vocal in essence.

weights are also agreed by consensus. Correlation between criteria is avoided as much as possible (Yoe, 2002; Keeney and Raiffa, 1993). Fourth, alternatives are evaluated using the additive model of multi-attribute utility theory (Fishburn, 1966), implemented in the TNA with an Excel® worksheet programmed for such a task. Inter-comparison of weighted scores obtained for alternative technologies give their rank order, whereby the technology associated with the highest score is ranked topmost and others follow in logical sequence. Sensitivity analyses of technology rankings are carried out when there is a marginal difference between ranked scores of two or more technologies or an answer is required to settle a hypothetical question. The procedure consists of MCA participants experimenting with non-random changes to criteria weights and evaluating the impact of specific changes on results previously obtained. In practice, MCA participants agree on changes to criteria weights following a blinding procedure in which a moderator denies participants access to performance matrix of alternative technologies, to curtail bias, when proposals for changes in criteria weights are made or being discussed. Criteria weights agreed by consensus are used to compute a new score for each technology, and inferences drawn accordingly.

Chapter 3 Technology prioritisation for energy sector

3.1 GHG emissions and existing technologies of energy sector

Pending development of a national strategy for the development of statistics[8] (NSDS), or measuring, reporting and verification (MRV) mechanism recently agreed by the Conference of Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC), The Gambia, as a non-Annex 1 party to the said convention, aperiodically publishes its national inventory of greenhouse gases (GHGs) a year or two later after the data is collated. To this effect, findings of the most recent national GHG inventory published in the Second National Communication (SNC) under the UNFCCC (GOTG, 2012a) tracks back to the year 2000.

In the SNC, the energy sector, excluding the non-electricity sub-sectors (i.e. transport and domestic biomass burning) is shown to generate a wide spectrum of GHGs including 81.3Gg of carbon dioxide (CO_2), 0.003Gg of methane (CH_4), and 0.001Gg of nitrous oxide (N_2O). GHG emissions derived from electricity production statistics for the years 2000 through 2012 point to an increase of 82 to 97% during the period in reference (NAWEC, 2015; WAIS, 2015; Sahel Invest, 2005), assuming the carbon intensity of electricity generation has remained unchanged during the same period. Yet, it is worth noting that The Gambia's INDC (2015) project higher GHG emissions, due in part to historical GHG emissions used in that study (GOTG, 2012a).

Table 3.1 Estimated growth in GHG emissions in electricity sub-sector (2000 to 2012)

	Emissions (Gg)			GWP	GHG emissions (GgCO$_2$-eq)			
GHG	2000†	2012*	2012*		2000†	2012*	2012*	2012‡
		Lower bound	Upper bound			Lower bound	Upper bound	
CO_2	81.3	148.1	160.4	1	81.3	148.1	160.4	
CH_4	0.003	0.005	0.006	25	0.075	0.125	0.15	
N_2O	0.216	0.002	0.002	298	0.298	117.1	126.9	
Total					81.673	265	287	400

Sources:
† GOTG, 2012a
* This Report‡ GOTG, 2015

Data on renewable energy installations based on wind and solar technologies is sketchy, but deployment is still limited. The electricity sub-sector is dominated by the National Water and Electricity Company (NAWEC) with its 101 MW installed capacity based on diesel-, light fuel oil (LFO) and heavy fuel oil HFO) fired generators. Two small independent power producers using small-scale wind turbines with 250kW aggregate capacity, provide surplus electricity to the NAWEC-operated power grid through commercial arrangements governed by the Renewable Energy Act (2013).

---

[8] Including environmental statistics

3.2 Decision context

In The Gambia, public policy on energy security is spearheaded by the Ministry of Petroleum and Energy (MoPE). In carrying out its principal mandate, MoPE benefits from the collaboration of ministries responsible for environmental management (MOECCWWF), regional integration and investment promotion (MOTIRIE), amongst other key players, to ensure the operation of robust and efficient energy markets governed by the OMVG[9] Convention on the development of common infrastructure for rational exploitation of water resources of River Gambia (1978), Forestry Act (1998), Electricity Act (2005), Renewable Energy Act (2013), EIA Regulations (2014), Consumer Protection Act (2014) and other relevant legislation. Except for state-owned enterprises, importers, producers and distributors of energy products conduct their business in accordance with the Companies Act (2013). The first of two state-owned enterprises, NAWEC has legal authority for the generation of electricity and development of water supplies for domestic, public, industrial and agricultural purposes. NAWEC is also authorised to purchase electricity from independent power providers (IPPs) at prescribed feed-in tariff rates. Similar to private sector subsidiaries of international oil companies, the Gambia National Petroleum Company (GNPC) picks up petroleum products from its supplier's storage depot at Mandinary and sells the merchandise to consumers at retail outlets countrywide (GPA, 2014, WAIS 2015).[10] Forest biomass products are harvested by operators licensed under the Forestry Act (1998) and sold to households through a vast network of middlemen and retailers in urban and peri-urban neighbourhoods. Compliance with the law including safeguarding of service standards, public safety, private sector participation and stakeholder engagement is monitored by the Public Regulatory Authority (PURA) and sectoral ministries with oversight of the National Assembly.

As alluded to in the previous paragraph, the Gambia has twin energy markets built around traditional and modern energy fuels and carriers, operating in parallel. On one hand, forest biomass fuels are predominantly used to satisfy a large part of household energy needs country-wide. By contrast, modern energy markets are constructed around direct and indirect use of petroleum products in automotive applications and electricity generation, respectively. According to IRENA (2013), forest biomass accounts for about 60% of the country's energy supply and more than 90% of household energy consumption, petroleum products[11] for 36%, and electricity for about 4% of energy supply. Data on renewable energy installations using wind and solar technologies is sketchy, but production is still marginal (Njie, 2015). Installed capacity for electricity generation by NAWEC in a distributed and partially connected national grid is 101 MW, producing 251GWh of energy and servicing 46% of the population. Power produced is conveyed to users first through an electricity grid comprising a 181-km long hybridised 33kV/11kV transmission network, step-down transformers, and finally through 230V and 400V distribution lines (NAWEC, 2015). Apart from infrastructural issues, the performance of the modern energy sector is thus entirely dependent on the reliability of supply

---

[9] French acronym for Gambia River Basin Development Organisation

[10] "*The petroleum sector is effectively unregulated in the Gambia, except for the price formula for market stabilisation. The sector is largely self-regulated by the four major companies, Total, Galp, GNPC and Elton oil*" (WAIS, 2015)

[11] This includes liquefied petroleum gas for cooking; diesel and heavy fuel oil for generating electricity

chains and world market prices for imported petroleum products. Suppressed demand for electricity estimated by AF-MERCADOS EMI (2013) is estimated to be about 194GWh. Under a historic expansion scenario, IRENA (2013) postulates a further widening of the gap between electricity supply and demand in the future. Buttressed by recent studies confirming the Gambia's potential in solar energy development (IRENA, 2013; Lahmeyer International, 2006; AF-MERCADOS EMI (2013)[12] and positive experience with the operation of two grid-connected small-scale wind turbine generating at Batokunku[13] and Brusubi,[14] the argument for upscaling renewable technology installations is a compelling one. Still, the following key issues central to the modernisation of the energy sector need further investigation: 1) spatial and temporal distributions of wind velocities at utility scale turbine heights; and 2) feasibility of biomass or waste as feedstock for electricity generation.

Current energy policy (2014-2018) in the Gambia with implementation spearheaded by the Ministry of Petroleum and Energy (MoPE) has multiple objectives centered on expanding energy supply systems, while simultaneously reducing the country's dependence on forest biomass and imported petroleum products in favour of renewable energy and natural gas. In recognition of the leverage energy systems have over economic development and social progress, the policy seeks to further diversity energy supplies and markets through regional integration initiatives with greater participation of the private sector.

From the foregoing, MoPE and key actors faces multiple challenges in ensuring delivery on government of the Gambia's commitment to the ECOWAS White Paper on energy for all by 2030 (WAIS, 2015). In this regard, the WAIS (2015) and AF MERCADOS (2013) are highly instructive. For the purpose of brevity, the major challenges are listed as follows:

1) meeting rapidly growing demand for all forms of energy (associated with greater mobility, population growth, urbanisation and economic activities);
2) reducing pressure on forest biomass and inefficient uses of other energy resources;
3) reducing the heavy reliance on imported petroleum products to meet the country's energy requirements;
4) minimising environmental impacts of energy supply;
5) cutting down lead times from feasibility studies to development of energy infrastructure; and
6) overcoming barriers to investment and human resources capacity constraints which have led to a progressive decline in the quality of services (NAWEC, 2015; WAIS, 2015).

Additional challenges for accelerating electrification rates and reducing tariffs, rooted in commercial sustainability of the operations of NAWEC and IPPs, comprise *inter alia,*

7) sizeable reduction of transmission losses (NAWEC, 2015);

---

[12] The Gambia enjoys high solar radiation in all regions with average solar emission at 4.4-6.7 kWh/m2/day (IRENA, 2013)

[13] communally owned (capacity 150kW, USD220,000 investment)

[14] privately owned

8) rapid deployment of cleaner and competitive supply solutions (Njie, 2015; IRENA, 2013, AF MERCADOS, 2013);
9) continually replenishing of scientific and engineering workforce;
10) leveraging domestic financing and scientific and engineering competencies to expand renewable energy sub-sector; and
11) further research on wind potential.

In light of the government's recent policy stances on the greening the country's economy and global effort on reducing GHG emissions (Urquhart, 2016, 2015; Lamour, 2013), the TNA analysis offers further insights into potential technological interventions, guided by a raft of performance metrics mutually agreed by key stakeholders. Specifically, analyses carried out under the TNA project helped identify technologies that are critically important for successful implementation of the country's LECRDS and INDC. Notwithstanding technological interventions, it is important to put in place complementary measures including policy changes/legislative amendments, economy-wide energy conservation measures, routine operation and maintenance (O&M) embedded within dynamic asset management processes and positive behavioural responses to climate change education could significantly augment the environmental impact of climate-friendly energy generations solutions that might be introduced in the future.

3.3 An overview of possible mitigation technology options in the electricity sub-sector and their mitigation potential and other co-benefits

Work needed to overcome challenges mentioned in previous section might be aptly viewed as discovery, prioritisation, implementation and impact assessment of climate-friendly and sustainable energy solutions. In addition to improved planning processes and implementation modalities in the electricity sub-sector, the body of evidence in recent studies and appraisals (Lamour, 2013; AF MERCADOS, 2013; IRENA, 2013) highlight the need for technological innovations making less use of primary energy sources, and/or harvesting of renewable and less-polluting energy sources. At the moment, power generation in the electricity sub-sector, which is the subject of analysis, is dominated by fossil fuel-fired utility-scale generators.[15]

Taking cue from several studies (Lamour, 2015; AF MERCADOS, 2013; IRENA, 2013; Lahmeyer International, 2006), this analysis proposes solar photovoltaic (PV), combined cycle, wind and hydrokinetic technologies for assessment as potentially cleaner power generation solutions.

Power plants based on the operation of technologies that use solar radiation or the kinetic energy of wind and tidal streams, have abatement potentials equivalent to emissions ordinarily generated by fossil fuel-fired generators having a similar power output. Taking the example of a 6MW plant, a solar PV power plant that is optimally located in the Gambia has the potential to reduce CO_2 emissions by 12Gg/year, compared to 4.6Gg/year and

---

[15] Some households, most major business and some government offices own smaller stand-by generators (2.5 to 400KVA) and use these as back-up powers solutions during power outages.

9.2Gg/year for a wind farm or tidal farm, respectively.[16] AF MERCADOS (2013) reports that emissions could be cut by 623GgCO_2 over the next 15 years by increasing renewable electricity generation to around 6.8% of expressed demand. To put these numbers into context, the INDC emission reduction target for renewables is approximately 200 GgCO_2, to be achieved by 2025. Elimination of petroleum products from the electricity generation process concomitantly eliminates air pollution,[17] waste oil and sludge management problems. Whereas a combined cycle diesel generation plant reduces fuel and associated emissions by 6%, it has the advantage of more reliable power generation, compared to renewable technologies based on unstable/variable intensity energy fluxes.

3.4 Criteria for technology prioritisation in electricity sub-sector

Eleven criteria are identified to gauge the relative merits of alternative power generation technologies earlier mentioned. These criteria, shown in Table 3.2, reflect environmental, social and economic incentives for and/or corresponding impacts of their deployment, as well as technical attributes mirroring performance of the specific technologies.

Table 3.2 Evaluation criteria for ranking power generation technologies

Criteria	**Units**	**Category**	**Description**
Investment cost	USD	Economic	expenditure required to: 1) purchase property and fixed assets; and 2) procure initial, additional, or replacement equipment, to meet specific operational objectives of entity making the investment
Safety	Ordinal	Social	*describes the condition of* freedom from perils and injury. Exposure to health hazards may be acute or chronic.
Efficiency	%	Technical	input-output ratio of an energy conversion technology
Land use	ha	Environmental	exclusion area required to install and operate specific technologies
HR capacity	Ordinal	Technical	level of competence of national workforce required to sustain satisfactory operation of specific technologies
Durability	Years	Technical	*reflects the* longevity/useful life of technological assets
Noise[18]	dB	Environmental	intensity of sound emitted from particular/multiple sources to which humans (outside the exclusion zone)[19] are exposed
Emissions	tCO_2-eq/yr	Environmental	quantity of non-fluorinated greenhouse gases released into the atmosphere by particular activities serving specific societal and economic functions
Employment	Ordinal	Social	new employment opportunities created by introduction of particular technology
Reliability	%	Technical	degree of dependability of technical assets measured as 100 – α, where α encapsulates breakdown frequency or level of underperformance of technical assets
Acceptability	Ordinal	Social	prospect of approval or acceptance of a particular technology depending on its relationship with socio-cultural values and norms, or public policy

---

[16] Although Lahmeyer (2006) conservative estimates of aeolian technology capacity factors are adopted by this author, AF MERCADOS (2013) suggests these could be higher taking cue from pioneering work by QCell.

[17] In addition to GHG emissions reported in section 3.2, power plants emit unquantified amounts of SO_2, CO, NO_x and particulate matter

[18] Sound intensity above constant roar of heavy traffic (90dB) can cause temporary loss of hearing, which left untreated can lead to permanent impairment (Ryding, 1992; http://noisepollution.weebly.com/measurement.html)

[19] Where relevant, employees should abide by Safety and occupational health guidelines

3.5 Results of technology prioritisation for the electricity sub-sector

Results presented in this section of the report emanate from implementation of procedures for technology prioritisation described in section 2.3. For the Gambian electricity sub-sector, a weighted sum of scores computed for four alternative large-scale electricity generation technologies is shown in column 2 of Table 3.3, wherein combined cycle diesel generation and wind turbine technologies are ranked as the top two technologies (See Annex III for computation details).

Table 3.3 Results of multi-criteria analysis (MCA) of electricity sub-sector technology options

Option	Weighted Score	Rank
Utility-scale Solar PV	48.8	3
Wind Turbine	69.8	2
Tidal Stream Generator	34.3	4
Combined Cycle Diesel Generator	76.5	1

To test the robustness of findings reported In Table 3.3, sensitivity analyses driven by selective and deliberative modifications of category and individual weight of technical, social, economic and environmental criteria shown in Table 3.4 were conducted. In the first of two sensitivity analyses (i.e., Run 1), aggregate economic and environmental criteria weights were downgraded compared to technical and social criteria under the Base Case (i.e., input data resulting in Table 3.3). In Run 2, MCA participants assigned economic and technical criteria with higher aggregate weights, whilst keeping the overall weight of environmental criteria unchanged *vis-à-vis* the Base Case. MCA results based on two sets of modified criteria weights and recorded as Run 1 and Run 2 in Table 3.5 show no changes in the ranking of competing technology options (See Annex III for detailed computations). The MCA thus concludes by confirming combined cycle diesel generators and wind turbines as the top two mitigation technologies in the electricity sub-sector, under the current TNA.

Table 3.4 Changes in overall criteria weights feeding into sensitivity analysis of MCA results reported in Table 3.3 (Base Case)

		Base Case		Run 1		Run 2	
Criteria	**Category**	Category weight	Individual weight	Category weight	Individual Weight	Category weight	Individual Weight
Efficiency	Technical	25%	8%	30%	10%	30%	10%
Reliability	Technical		5%		6%		6%
Durability	Technical		5%		7%		7%
HR capacity	Technical		7%		7%		7%
Safety	Social	25%	9%	30%	12%	15%	6%
Acceptability	Social		12%		13%		7%
Employment	Social		4%		5%		2%
Cost	Economic	25%	25%	25%	25%	30%	30%
Land use	Environmental	25%	8%	15%	3%	25%	8%
Noise	Environmental		4%		2%		4%
Emission	Environmental		13%		10%		13%

Table 3.5 Sensitivity analysis of MCA findings on electricity sub-sector technology options

Option	**Weighted score (Table 3.3)**	**Sensitivity Analysis**	
		Run 1	**Run 2**
Utility-scale Solar PV	48.8	49.8	42.8
Wind Turbine	69.8	68.3	71.1
Tidal Stream Generator	34.3	30.3	36.5
Combined Cycle Diesel Generator	76.5	79.2	77.2

Chapter 4 Technology prioritisation for transport sector

In response to the scope of transport policy analyses, passenger and freight transport issues are usually studied on a modal, possibly intermodal and less frequently on an integrated basis.[20] Similar to countries with navigable water bodies, operational modes of water, land, and air transportation provide diverse passenger and freight services in The Gambia. Due to the country's geography, economic and trade policies, part of the said passenger and freight traffic is domestic whilst a significant part is international in scope.

In 2014, the port of Banjul provided berthing facilities for dozens of ships sailing under international flags with gross tonnage of 4.5 million metric tonnes and cargo throughput 1.9 million metric tonnes in 2014 (GPA, 2014). Similarly, Banjul international airport handled 3,798 flights with a total throughput of 331,322 passengers, and cargo of 1,792 metric tonnes (GCAA, 2015). During the same year, approximately, 295,630 registered visitors[21] travelled by road to the Gambia (GTB, 2015). Crucially, domestic road travel provides more than 15 million passenger-journeys annually for the county's population, mostly domiciled within a distance of 40km from the capital, Banjul. Roll-on roll-off (ro-ro) ferries plying between Banjul and Barra and motorised pirogues, the latter especially during peak demand periods, provide an alternative means for moving people and goods between the North Bank of the river Gambia and Banjul. In the technology assessment that follows, the focus is on vehicular road transport due to scale issues,[22] growth dynamics and contributions to GHG emissions (GOTG, 2012a)

4.1 GHG emissions and existing technologies of transport sector

Despite the growing number of road vehicles and associated threats of vehicle emissions to human health, especially in areas occupied by large numbers of people, measurements of air pollutants[23] and GHG inventories have largely been peripheral issues in transportation planning, road traffic management, and climate protection.

In a recently published national GHG inventory however, the transport sector emerged as a bigger emitter of GHGs than energy generation industries in the year 2000 (GOTG, 2012a)[24]. According to a historic reconstruction of GHG emissions in the transport sector, total emissions grew by 111% between 2000 and 2012 (GOTG, 2015). Using data on fuel imports (WAIS, 2015) extrapolated to 2012, the current assessment estimates CO_2 emissions of 272.9Gg in 2012, representing a 175% growth between 2000 and 2012.[25]

---

[20] Integrated analyses are likely to reveal completive advantages (cost, speed, reliability, safety, etc.) individual modes as well as opportunities for complementation

[21] This number excludes persons using tertiary and unclassified roads to travel back and forth across the Gambia-Senegal border on family-, cultural-, business-, or religious-related activities.

[22] The Gambia has no merchant marine fleet, but is home to hundreds of pirogues fitted with outboard engines constitute the artisanal fisheries fleet. The average distance to fishing grounds is 100 km on one round-trip. . The largest vehicles used in water transport link the North and South banks of the river through the capital Banjul has an approximate throughput of 1.5 million passengers and 600,000 tonnes of freight on roughly 6,000 metric tons of fuel consumed yearly.

[23] including GHGs such as CO, SO_2, NO_x.

[24] wherein GHG emissions data from the transport sector is officially reported for the first time

[25] It is assumed that fuel consumed is equivalent to imports less one month reserve, that is 92% (=12/13) of total imports. Still, there is some uncertainty about how much of these emissions is attributable to portable

Estimated emissions of nitrous oxides (NO_x) are more tricky because of their dependence on vehicle type and travelling speeds.

Table 4.1 Estimated growth in GHG emissions in transport sector from 2000 to 2012

	Emissions (Gg)		GWP	GHG emissions GgCO$_2$-eq)		
GHG	2000†	2012*		2000†	2012*	2012‡
CO_2	99.0	272.9	1	99.0	272.9	
CO	5.812	6.793	n/s	n/c	n/c	
NO_x	1.68	n/a	n/s	n/c	n/c	
Total				99.0	272.9	210.0

Key: n/s = not specified in literature; n/a = data not available, n/c = not computable

Sources:

† GOTG, 201a

* This Report

‡ GOTG, 2015

The national vehicle fleet is almost entirely made up of vehicles fitted out with internal combustion engines. According to transport sector operatives, more than 60% of vehicles (of all categories) use spark ignition technology. Vehicle using compression ignition technology is slightly less common yet disproportionately represented among heavier vehicles (Pers. Comm., Fallou Jobe, Automobile Mechanic).

4.2 Decision context

In 2014 overall responsibility for policy development, strategic guidance and operational oversight of the transport sector was assigned to the Ministry of Works, Construction and infrastructure (MOWCI), then renamed Ministry of Works, Transport and infrastructure (MOWTI). Working through public sector agencies and strategic partners, chiefly its subsidiary executive agency, the National Roads Authority (NRA), MOWTI is responsible for the construction and classification of all roads and prescribing operational rules including health and safety standards. In turn, the NRA Act (2007) makes provisions for partial delegation of NRA road construction responsibilities to local authorities with the approval of relevant government ministers. Its antecedent role in road construction is ceded to private sector operatives, and NRA now acts more as a consultant to government.

The Gambia Police Force (GPF) is responsible for motor vehicle registration, traffic management and enforcement of environmental and safety standards especially those relating to speed limits and tailpipe emissions of "black smoke" (Njie, 1996).[26] GPF officials also compile accident statistics which are published by the Gambia Bureau of Statistics (GBoS). In consideration of planning laws, in particular the Department of Physical Planning and

---

generators, compressors, lawn mowers, and other non-transport equipment operating on diesel fuel. On the other hand, activity data and key assumptions for transport sector are not provided in worksheets supporting GOTG (2015)

[26] Note that emission standards are not in place and this rule is not strictly enforced. The national Environment Agency (NEA) briefly piloted an air quality monitoring programme measuring NO_2, SO_2, PM_{10}, but the programme has been discontinued due to repeated instrumental breakdown and unsustainably high capital and operational costs.

Housing Act (1988) and EIA Regulations (2014), local government authorities (LGAs) establish exchange hubs/car parks in strategic locations within the Greater Banjul Area (GBA) and major towns (Njie, 2015; 2014). Passenger and freight drivers' associations are not very active judging from their lack of visibility in public discourse on transport policy.

Domestic vehicle population of passenger-[27]and freight-carrying transport[28] number approximately 70,000. Overall, the transport sector is characterised by a high level of private and distributed ownership of both freight and passenger vehicles.[29], [30] A significant proportion of these provide passenger services to people commuting to work and others going about their daily business. In the densely populated Kanifing Municipality, a sizeable and increasing population of bicycles, and to a lesser extent, mopeds, provides personal mobility for some people living considerable distances from routes normally served by public transport and taxis. A handful of car rental services cater to a niche market of holiday-makers and business executives.[31]

Judging from the expansion of used-car dealership businesses, it can be concluded that most vehicles joining the national fleet are used cars typically 10-15 years old. Exceptionally, government entities, large corporations and a few private buyers resort to procurement from dealers with franchises from EU or Asian manufacturers. Amidst vehicle population growth patterns, NRA (2014) reports an average daily traffic of around 100 vehicles on rural feeder roads, 225 vehicles on interurban roads, and 2,400 vehicles along the Banjul-Brikama axis. In parallel, imports of petroleum products has steadily risen (WAIS, 2015), spurring in principle, a sharp increase in CO_2 emissions from the transport sector.

The combination of high vehicle numbers and limited road capacity, compounded by traffic management deficiencies, contributes to congestion along main road arteries within the Greater Banjul Area (GBA), increased travel times, higher fuel consumption, and CO_2 emissions,[32] with unquantified economic and health impacts on road users and local communities. Other causal relationships remaining unchanged, it is reasonable to assume that traffic congestion problems will get worse with a growing vehicle fleet population.

Transport mobility is an indispensable feature of modern living,[33] but road transport has some drawbacks that deserve attention. Specifically greenhouse gases emissions, air pollution and noise problems need to be addressed. For instance, fuel efficiency lies at the

---

[27] cars, pick-up, vans, and buses

[28] flat-bed trucks, tanker-trucks, tippers, etc

[29] Exact statistics for vehicular road transport are difficult to obtain from GPF. The need for a centralised and comprehensive database is acknowledged in the National Roads Authority Strategic Plan and the Gambia government's national energy efficiency action plan (GOTG, 2015) championed by the Ministry of Energy and Petroleum. There are no restrictions on routes served by drivers/owners or number of vehicles owned by individuals.

[30] Following the collapse of the Gambia Public Transport Corporation, the Gambia Transport Service Corporation (GTSC), a subsidiary of Social Security and Housing Finance Corporation (SSHFC), a state-owned enterprise, was established in 2013, and now operates a fleet of 53 passenger and school buses, all combined, across the country.

[31] http://www.accessgambia.com/car-hire.html

[32] Persistent bottlenecks at security checkpoints during morning/evening rush hours also result in significant tailbacks, travel delays and increased CO_2 emissions

[33] Observational evidence shows that despite altruistic traditions of non-commercial vehicle drivers/owners giving free rides to would-be stranded travelers/commuters, access to transport services remains a daily challenge for hundreds if not to say thousands of people moving from one place to another.

heart of the quest for technical/technological solutions to reduce escalating vehicle emissions. In contrast to EU fuel efficiency standards of 5.6 litres/100 km,[34] the average light-vehicle in the Gambia uses 20 to 30 litres for 100km of travel (Pers. Comm., Fallou Jobe, Engine Mechanic; Kabaa Fatty, Driver). Additionally, the quality of transport services, such as predictability, fluency, comfort and safety[35] might require closer scrutiny by major stakeholders in government and private sector operators. In support of transport sector objectives, a partial modal shift from road to urban water transport with a view to increasing passenger flow capacity during rush hours, is also worthy of consideration. As yet, MOWTI has no fully developed transport policy, but pronouncements on an official website embrace the vision of a national transport policy that augments the productive capacity of the economy and contributes to improvement in citizens' living standards. As for road transport in particular, the main objective is to improve the quality of passenger and freight transport services. To this end, the NRA strategic objectives include the establishment of a central database on transport information, and capacity enhancement of homogeneous target groups, in order to transform service delivery for the better.

From the foregoing, the top *six* challenges for road transport sub-sector from a climate change and sustainable development perspective are as follows:

1) increasing the proportion of vehicles with a lower carbon footprint in the national fleet;
2) improving traffic management strategies to ease movement of people and goods and cut down on vehicle fuel consumption;
3) strengthening system (s) for vehicle registration and driver licensing;
4) regulating overloading and overcrowding of vehicles (NRA, 2014);
5) expanding road infrastructure and improving its quality (NRA, 2015; Greene et al., 2013, Beuving et al., 2004); and
6) ensuring cross-sectoral policy coherence .[36]

In light of road transport sub-sector objectives and constraints, the TNA systematically evaluates the strengths and drawbacks of a limited set of mature and emerging climate-friendly technologies to shed light on their relative merits for cutting GHG emissions in general, and delivering the INDC emission reduction target of 114Gg CO_2-eq by 2025 in particular.

It is important to highlight that positive environmental impacts of technology could be further enhanced through value-for money road construction and maintenance programmes, a robust vehicle inspection regime, and phasing out of older vehicles. In the matter of vehicle fleet renewal, government entities' demonstrated leadership in the procurement of vehicles that meet specified emissions standards would be an excellent point of departure. Cognisant of inadequate passenger vehicle stock however, implementation of a vehicle renewal policy should be reasonably paced to avoid social and economic disruptions as much as possible.

---

[34] http://www.unep.org/transport/gfei/autotool/case_studies/europe/cs_eu_0.asp

[35] Driver skill and discipline

[36] climate change, fiscal, public health, infrastructure, spatial planning, environment, etc.

4.3 An overview of possible mitigation technology options in the road transport sub-sector and their mitigation potential and other co-benefits

Apart from material science innovations and vehicle aerodynamic design parameters that influence drag resistance and fuel consumption, two broad technological categories, namely, fuel-saving and electric powertrain technologies, are potential remedies to growing vehicular emissions.

Direct injection technology, the first of four options, significantly increases fuel efficiency and power output of internal combustion engines, compared to conventional carburetted engines. Turbochargers similarly increase fuel efficiency and power output, but do so by optimising airflow into the engine-mounted combustion chambers. Abatement potential of either technology ultimately depends on the number of vehicles that are fitted with a particular technology and their aggregate travel distances. On a vehicular basis, these new fuel-saving technologies are expected to deliver a 10-15% reduction in GHG emissions.

Elimination of vehicular noise and tailpipe emissions of GHGs, particulate matter and other pollutants[37] account for the biggest advantages of battery-powered electric vehicles (BPEV) and fuel cell electric vehicles (FCEV). Indeed, BPEVs have no tailpipe, but unless they use electricity generated from renewable sources, their overall impact on emissions reduction is around 40% compared to an ordinary diesel-powered car engine (Thiel et al., 2010). With all technology options, reduced fuel or energy consumption per distance of travel directly results in cost savings, and improved air quality.

4.4 Criteria and process of technology prioritisation for the road transport sub-sector

Technology prioritisation for the transport sector uses eleven criteria described in Table 4.2. Criteria reflect environmental, social and economic impacts of technology deployment, as well as technical attributes mirroring performance of proposed technologies.

Table 4.2 Evaluation criteria for ranking road transport technologies

Criteria	Units	Category	Description
Investment cost	USD	Economic	expenditure required to: 1) purchase property and fixed assets; and 2) procure initial, additional, or replacement equipment, to meet specific operational objectives of entity making the investment
Safety	Ordinal	Social	*describes the condition of* freedom from perils and injury. Exposure to health hazards may be acute or chronic.
Efficiency	%	Technical	input-output ratio of an energy conversion technology
Operational cost	USD	Economic	recurrent expenditure on fuel/power for operations, maintenance and or leasing of equipment, and other service fees, made by owner/operator of productive technical assets
HR capacity	Ordinal	Technical	level of competence of national workforce required to sustain satisfactory operation of specific technologies
Durability	Years	Technical	*reflects the* longevity/useful life of technological assets
Noise[38]	dB	Environmental	intensity of sound emitted from particular/multiple sources to

---

[37] Indeed, BPEVs have no tailpipe, but unless they use grid electricity generated from renewable sources, their overall impact on emissions reduction is attenuated.

[38] See footnote 20

Criteria	Units	Category	Description
			which humans (outside the exclusion zone) are exposed
Emissions	tCO_2-eq/yr	Environmental	quantity of non-fluorinated greenhouse gases released into the atmosphere by particular activities serving specific societal and economic functions
Fuel economy	MPG-e/100km	Technical	reflects relationship between distance travelled by a vehicle and fuel or comparative amount of energy used
Fuelling time	minutes	Social	time required to get an internal combustion engine vehicle refuel, or battery of alternative electric vehicle fully charged
Diffusion time	Years	Social	quantum of time its take for a novel technology to be adopted by at least 80% of potential users

4.5 Results of technology prioritisation for the road transport sub-sector

Results presented in this section of the report derive from implementation of procedures described for technology prioritisation in section 2.3. According to weighted scores and corresponding rank order of road transport technologies reported in Table 4.3, direct fuel injection systems and turbochargers embody the two top prospective mitigation technologies in the road transport sub-sector.

Table 4.3 Results of multi-criteria analysis (MCA) of road transport sub-sector technology options

Option	Weighted Score	Rank
Direct fuel injection	65.8	1
Turbocharger	62.2	2
Fuel cell electric car	51.6	3
Battery-powered electric car	33.8	4

To test the robustness of findings reported in Table 4.3, one additional analysis was conducted using modified group and individual social and economic criteria weights. In this additional analysis (Run1), social and economic criteria weights in the approximate ratio of 1:2 were swapped, and MCA computation results shown in Table 4.5. In this table, the rank order of technologies in Run 1 is unchanged *vis-à-vis* the Base Case thus confirming direct fuel injection systems and turbochargers as the top two mitigation technologies in the road transport sector.

Table 4.4 Changes in overall criteria weights feeding into sensitivity analysis of MCA results reported in Table 4.3 (Base Case)

		Base Case		Run 1	
		Category weight	Individual weight	Category weight	Individual Weight
Criteria	**Category**				
HR capacity	Technical	25%	6%	25%	6%
life span	Technical		11%		11%
Fuel efficiency	Technical		8%		8%
Fuelling time	Social	34%	9%	16%	3%
Diffusion time	Social		12%		6%
Safety	Social		13%		7%
Vehicle cost	Economic	16%	11%	34%	19%
Fuelling cost	Economic		5%		15%
Emissions	Environmental	25%	18%	25%	18%
Noise	Environmental		7%		7%

Table 4.5 Sensitivity analysis of MCA findings on road transport sub-sector technology options.

Option	**Weighted score (Table 4.3)**	**Sensitivity Analysis**	
		Run 1	
Direct fuel injection	65.8	59.8	
Turbocharger	62.2	56.8	
Fuel cell electric car	51.6	52.9	
Battery-powered electric car	33.8	37.8	

Chapter 5 Technology prioritisation for waste sector

Domestic, agricultural, industrial and medical wastestreams[39] generated from consumption of natural capital, or production of manufactured capital by units of production and consumption,[40] often have potentially deleterious effects on environmental and human health. Under particular circumstances, a fraction of specific wastestreams might be reused for some other purpose, but the generality of waste residues are eventually disposed of. The fate of waste so disposed or stored depends on the receiving/repository medium's capacity to break down and disperse wastestreams into more environmentally benign concentrations or components through natural transport and transformation processes.

For pragmatic reasons, the focus of the analysis that follows is on municipal solid waste (MSW) in the Greater Banjul Area, where management challenges linked to this wastestream has reached epic proportions (NEA, 2010). Compared to homogenous wastestreams from industrial and agricultural activities, it should be noted that MSW[41] comprises a complex assortment of wastes.

In the Gambia, air quality protection is constrained by the absence of emission standards, inadequate technical assets, a weak workforce of scientific and engineering professionals, and economic agents' disengaged responses to environmental education. By contrast, water quality standards, under a proposed Water Resources Management Act (2014) and existing regulations under the National Environmental Management Act (1994), address some types of effluent discharges. Wastewater is discharged into the natural environment through diffuse surface drainage, and point sources such as latrine pits and soakaways located in residential developments and office blocks, and sewage outfalls under the control of NAWEC (Njie, 2014).[42] Nonetheless, Njie (2009) observes that environmental monitoring stations are sub-optimally located and monitoring protocols do not cover for instance heavy metals, organic compounds, or non-aqueous phase liquids (NAPLs). Consequently, competent authorities need to assiduously work on operationalising the polluter-pays principle asserted in the National Environmental Management Act (1994), echoed by the Sanitation Policy (2009), and re-asserted by the National Climate Change Policy (2015). In such a context, Njie (1996) recommends a game-theoretic approach to verify/reward compliance and punish/sanction violations following spot checks/environmental audits, keeping in mind resource constraints facing regulatory institutions.

---

[39] These comprise of gaseous, liquid (wastewater with or without non-aqueous phase liquids), slurry, sludge, and solids. For a comprehensive segmentation and differentiation of wastestreams, see EIA Guidelines (1996)

[40] Households, businesses, government entities

[41] "MSW is made up of biodegradable, non-biodegradable and a tiny fraction of non-categorised discards

[42] NAWEC provides sewerage services for the city of Banjul. Dry weather flow from this system ranges varies from 10,500 to 14,600m^3/day, and increasing by20 to 25% approximately during high intensity rainfall. From a diffuse catchment area[42] within the Kanifing Municipality, NAWEC also operates stabilisation ponds in Kotu serving a maximum population estimated at 50,000 people. Outflow from these treatment works is between 1,000 and 2,700m^3 of effluent/day. Elsewhere, labyrinthine roads and unplanned housing configurations represent a huge challenge to provision of basic services. Indeed, installing modern sewage systems in these areas may no longer be feasible and protection of groundwater resources from sub-surface pollution becomes imperative. Note that Kotu oxidation ponds receive wastewater from the Tourism Development Area (TDA) and discharges by sewage tankers operating throughout the Kanifing Municipality on a demand/contractual basis.

5.1 GHG emissions and existing technologies of waste sector

It is worth noting that emissions of carbon dioxide (CO_2), carbon monoxide (CO), and nitrous oxides (NO_x) from waste burning, a low-intensity form of incineration, is not included in the Gambia's national communications for lack of pertinent data (GOTG, 2012a; 2012; 2003). This study draws attention to data quality issues surrounding methane (CH_4) emissions. Whereas aperiodic GHG inventories reflect a slump in CH_4 emissions from official dumpsites from 9.39 to 6.51Gg between 1993 and 2000, the Gambia's INDC (GOTG, 2015) reports emission rates of 1.68 and 2.40 Gg for corresponding years.[43]

This TNA report builds on waste data from the 2004 World Bank Waste Survey cited in NEA (2010) and computational parameters found in the Gambia's First National Communication (GOTG, 2003),[44] to reconstruct CH_4 emissions shown in Table 5.2. Table 5.1, an intermediate first step towards reconstruction of CH_4 emissions, gives statistics of waste deposited at official dumpsites.

Table 5.1 Quantities (mt) and sources of MSW deposited in official dumpsites.

	Year	Banjul	KMC	Brikama	Kombo North	Kombo South	GBA‡
Generated (mt)	1963	5,481	2,406	827	1,822	0	10,536
	1973	7,722	7,767	**1,788†**	3,292	0	20,569
	1983	8,709	20,282	3,868	6,563	0	39,422
	1993	8,342	44,981	8,231	15,472	7,824	84,850
	2003	6,911	63,611	11,344	32,816	12,144	126,826
	2012	4,459	91,831	16,196	50,618	16,465	179,569
Fraction collected[45]		1.00	1.00	0.80	0.50	0.50	0.80
Total collected & disposed (mt)		4,459	91,831	12,957	25,309	8,232	142,788

Source: This Report

Notes

†Data (mistakenly) reported as nil in NEA (2010). Estimated quantity is the geometric mean of waste generated in 1963 and 1983.

‡ Row sum of Banjul, KMC, Brikama, Kombo North and Kombo South data.

Reconstruction of 2012 data is based upon second-degree polynomial projections of Banjul, Kanifing Municipality, and Kombo North time series, combined with linear projection of Kombo South data.

---

[43] obtained by dividing reported emission values expressed in $GgCO_2$-e units by 25

[44] See Table 2.16 on page 27

[45] Author's assumptions informed by opportunities for and constraints to waste burial and burning, and emergence of environmental service providers

Table 5.2 Methane (CH_4) emissions from municipal solid waste decomposition.

Year	**MSW (mt)**	**DOC fraction**[46]	**CH_4 emissions (Gg)**	**Source**	**Remarks**
1993	119,510	0.255	9.36	GOTG (2003)	First National Communication (FNC) report uses default parameter value of 0.255 as dissolved organic carbon (DOC) fraction
1993	119,510	0.490	17.99	This Report	FNC reanalysis using biodegradable waste fraction derived from World Bank survey data reproduced in NEA (2010)
1993	-	-	1.68	GOTG (2015)	Obtained by dividing reported emission values expressed in $GgCO_2$-eq units by 25. Average of low and high emissions in INDC worksheets used
1993	71,556	0.490	10.77	This Report	FNC reanalysis using biodegradable waste fraction found in World Bank survey cited in NEA (2010) and variable geographical collection rates shown in Table 5.1
2000	-	-	6.51	GOTG (2012a)	
2000	-	-	2.40	GOTG (2015)	Obtained by dividing reported emission values expressed in $GgCO_2$-eq units by 25. Average of low and high emissions in INDC worksheets used
2000	114,233	0.490	17.20	This Report	
2012	-	-	12.72	GOTG (2015)	Obtained by dividing reported emission values expressed in $GgCO_2$-eq units by 25. Average of low and high emissions in INDC worksheets used
2012	142,788	0.490	21.50	This Report	

5.2 Decision context

In spite of their ubiquitous presence in all economic sectors, waste management activities and related challenges are acknowledged for the first time in countries' national accounts in ISIC Rev 4 (UN, 2008). Reflecting its distributed character in the Gambia, waste management is federatively carried out with some success by public institutions working at the intersection of public health, natural resources and environmental management, and land use policies.

In theory, backed by law, siting and sizing of MSW disposal facilities depends on the composition and quantity of waste. Key decisions in this matter lies separately or jointly with ministries responsible for public health, spatial planning, environmental quality and sub-national government. The Public Health Act (2008) requires the Ministry of Health and Social Welfare (MoHSW) to undertake measures to ensure the sanitary disposal of waste, which action calls into play land acquisition procedures under relevant provisions of the State Lands Act (1990) and Physical Planning and Development Control Act (1988), and possibly the Land Acquisition and Compensation Act (1991), administered by subsidiary agencies of the Ministry of Lands and regional Government (MoLRG). However, land allocation decisions cannot be finalised without subjecting potential facility locations to environmental and social impact assessments as required under EIA Regulations (2014) in accordance with

---

[46] of which 37% released as CH_4 (GOTG, 2003)

EIA Guidelines (1996).[47, 48] In this regard, decisions are jointly shaped by objectives and constraints articulated by technical institutions, regulatory institutions, administrative bodies, and communities within the vicinity of planned facilities, paying particular attention to probable consequences and risks of particular decisions and reversibility of those decisions. Three waste disposal facilities currently exist in the greater Banjul Area. Of these, only Tambana (Brikama Local Government Area) has gone through an EIA process, whilst establishment of the other two, Mile 2 (in Banjul) and Bakoteh (in Kanifing Municipal Area), predate serious expressions of environmental quality concerns in public policy.

Further synergies between the Public Health Act (2008) and Local Government Act (2002) strengthens Local Government Authorities' mandates in providing public services including waste management. In the Greater Banjul Area, a fraction of solid waste from homes/businesses/offices is collected and disposed by Banjul, Brikama and Kanifing municipalities using a small fleet of tractors and flat bed trucks inter-mingled with a few specialised waste-handling transport assets. Under an unwritten arrangement that provides convenience and relief to stakeholders, part of the solid waste that is not collected by municipal services[49] is picked up by public health and pest control service providers and offloaded at official dumpsites, for a mutually agreed fee.[50] Illegal dumping on land is prohibited under the Environmental Management Act (1994) and Public Health Act (2008). Although anti-littering regulations serve to restrain reckless tossers, they fail to eliminate a persistently litter-blighted landscape, attenuated in Banjul by street cleaning, and monthly voluntary cleanup exercises in Banjul and other places in the country.

Potential violations of conventions on the transboundary movement of hazardous waste are closely monitored by National Environment Agency and Customs officials. Likewise, the Gambia Navy supports the Gambia Maritime Agency in enforcing provisions of the Merchant Shipping Act (2013), Marine Pollution Act (2013), Environmental (Prevention of Dumping) Act (1988), and MARPOL (1973) on marine pollution caused by unauthorised dumping of wastes in Gambian waters.[51]

Waste disposal facilities, implicitly owned and operated by LGAs, currently function as open dumps.[52] Municipalities do not have security employees on site, and only Bakoteh has a perimeter fence. Upstream and on-site waste recycling by small entrepreneurs and scavengers, respectively, occurs on a small scale. The overwhelming bulk of MSW is allowed to build up and decay without any form of treatment. Deposited waste is often burnt

---

[47] "*Types of projects primarily fall into the following categories: conservation systems (including recycling, resource recovery, composting and source reductions); landfill and other treatment with gas recovery and leachate control (including sanitary landfill, landfill with gas recovery and use, landfill with separate disposal zones, anaerobic digestion, gasification, pyrolysis, etc.); incineration with air pollution control (including mass burn with energy recovery, refuse derived fuel production, separate incineration for medical wastes and incineration at sea for hazardous wastes); and, ocean disposal (including dumping of treated or untreated wastes from vessels)"* EIA Guidelines, 1996

[48] Mitigation measures may be required to offset or considerably predictable adverse impacts

[49] Size of vehicle fleet, operational budget, and accessibility to far-flung homes are key bottlenecks

[50] Notwithstanding, municipal/private employers of waste handling crews/teams and their supervisors are self-employed waste handlers are at best partially compliant with occupational health safety policy (2007).

[51] Violations are sanctioned by fines and/or imprisonment.

[52] Initially, Tambana was designated a sanitary landfill site receiving waste from nearly 100,000 households and businesses, but is suitability was questioned by quantitative risk assessment in the context of GBA water supply system extension. The site is now partly in use as a dumpsite for Brikama.

in open fires and occasionally compacted to augment dumpsite capacity and extend its service life, but monitoring of waste deposits for hazardous substances is not perceived to be any particular institution's responsibility. Long-term monitoring programmes or studies on environmental quality and human exposure to toxic substances emanating from waste treatment and disposal at the Bakoteh dumpsite in particular, do not exist either.

In general, waste emplaced at disposal facilities is not inventoried. What little is known about municipal solid waste (MSW) composition and quantities comes from Brown and Root Environmental (1994) and the 2002 Waste Survey Report cited in Sanneh (2013). It is thus estimated that GBA residents generate on a daily basis 0.54kg waste/capita. In the aforementioned waste survey report, MSW, by weight, is composed of 49% biodegradable, and 51% non-biodegradable matter. Of the non-biodegradable fraction, sand, glass and metals account for 46%, 1% and 2% of the total respectively. Households and businesses, to variable degrees, opt for burning or burial of uncollected waste. Health Centres operating under the MoHSW and Medical Research Council (MRC) use incinerators to neutralise hazardous medical waste.

Waste generation hotspots are not documented, but it is sufficient to point out that the quality of consumer goods on the market, household consumption and commitment to environmental quality protection (NEA, 2010; Njie 2014) are key determinants of solid waste generated. As population in the Greater Banjul Area continues to grow, and concerned voices get louder, it has become increasingly self-evident that new solutions to waste management problems are urgently needed. In this regard, abandonment of a proposed disposal facility at Tambana (near Brikama), due to significant risks of groundwater pollution, is a big setback considering the scarcity of suitable disposal sites.[53] The author has personal experience of processing water quality data from observation boreholes[54] downstream of Bakoteh dumpsite that show a plume of nitrate pollution from leachate, at the end of every rainy season. However, a bigger public health concern emanates from wastestreams containing persistent micropollutants. These include benzene hexachloride and lindane both of which were found in the soft tissues of shellfish in an area adjacent to the Mile 2 dumpsite in Banjul (Jallow, 1989). Likewise, waste burning by households in pits, barrels, or open fires constitutes significant health hazards.[55]

All facts considered, the most pressing challenges for solid waste management include *inter alia* the following:

1) timely waste evacuation from least accessible built-up areas without storage facilities;
2) developing a business model for the waste sector; [56]
3) attracting private investments to the waste sector (NEA, 2010);
4) continual improvement of local and central government entities' capacities for waste collection, handling and management;
5) environmental quality and public health policy integration on relevant sub-domains;[57] and

---

[53] The holding capacity of Bakoteh and Mile 2 dumpsites is closed to being reached.

[54] Borehole indicators, 1993 -1995 data archives

[55] Inefficient burning might produce carcinogenic furans, dioxins,

[56] having waste recycling and transformation as some of its key objectives

6) stimulation/reinforcement of positive behavioural changes towards waste minimisation, waste separation, casual littering.

In the absence of a specific policy for the management of solid and liquid wastestreams, the general drift of policy on waste management, informed by the Prevention of Dumping Act (1989), Public Health Act (1990), Public Health Regulations(1990), National Environment Management Act (1994), and Local Government Act (2002) is towards relocation of old dump sites to more appropriate locations and creation of landfills to better manage the ever-increasing solid wastestreams generated countrywide. However, the earlier part of this report and challenges enumerated above suggest that existing policy instruments still fall short of providing efficient multi-agent solutions to MSW management problems experienced in the country. This assessment is in line with Ryding (1992) who argues that effective waste management may entail creation of a specialised organisation responsible for the collection, transportation of waste and management of treatment and disposal facilities.

Analogous to other mitigation sectors in this report, one of the key objectives of the TNA assessment in the waste sector is to identify and prioritise a limited set of technologies capable of providing long-term solutions to MSW management problems in the Greater Banjul Area, and by extension, other growth poles[58] in the hinterland. Doubtless, proposed technological solutions can always be enhanced by effective community engagement, economic incentives and additional policy measures.

5.3 An overview of possible mitigation technology options in the waste sector and their mitigation potential and other co-benefits

Currently, waste disposal facilities within the Greater Banjul Area do not possess or employ any form of technology for purposeful waste treatment. As earlier mentioned, MSW deposited at officially designated dumpsites is allowed to build up and decay without any intervention. Waste that is not transferred to dumpsites but left on household premises is often burnt in pits, barrels, or open fires.[59] This analysis proposes landfill technologies, anaerobic digesters, incinerators and aerated pile composting as means of curbing fugitive methane emissions from large primitive dumpsites that do not incorporate safeguards for climate protection.

In addition to groundwater protection, elimination of nuisance factors and minimisation of health risks, sanitary landfill technology makes it possible to safely capture methane gas (from decomposing MSW) for use as an energy fuel, or, if not needed, oxidised using a flare system. However, emissions reduction largely depend on the efficiency of leakage control measures and methane capture sub-systems.[60, 61] Bioreactor landfills, a more

---

[57] The current health policy (2012-2020) is built around therapeutic/project interventions to address diarrhea, trachoma, respiratory tract diseases, which cannot be disconnected to environmental quality problems.

[58] Towns and larger villages gradually transformed by population and economic activity concentration into bigger and more vibrant administrative entities.

[59] Viability and use of these options declines with housing densification and access to private waste collection services

[60] Flaring, which coverts CH_4 to CO_2 could reduce the global warming potential of landfill emissions by 95%.

sophisticated form of sanitary landfill design, have added advantages of speeding up methane production and thus shortening landfill stabilisation timescales (Powell et al., 2006; Murphy et al., 1995).

Anaerobic digester technology replicates waste decomposition processes under anaerobic conditions. Thus, the technology is able to reduce landfill spatial requirements, reduce methane ordinarily emitted from primitive dumpsites and produce recyclable products. Moreover, anaerobic digesters can be deployed on a variety of scales and significantly reduce transportation costs. Waste incineration technology uses high temperatures to convert waste to heat, gas, steam and solid residue. Incineration of 1 tonne of MSW produces approximately 1 tonne CO_2, 67% lower than equivalent CO_2 production from landfills.[62] Incineration with energy recovery is one of several waste-to-energy (WtE) technologies such as gasification and pyrolysis. Incineration is particularly suited for hazardous waste, and quite attractive in situations of land scarcity. Diverting compostable material from landfill to composting operations, as a way of avoiding CH_4 emissions, could potentially deliver GHG emission reductions of about 83% (Brown et al. 2008). Aerated static pile composting is particularly suited for facilities processing wet organic materials and large feedstock volumes.

5.4 Criteria and process of technology prioritisation for the waste sector

A criterion set containing 11 criteria is identified to gauge the relative merits of MSW management technologies earlier mentioned. Individual criteria reflect environmental, social and economic impacts of technology deployment, as well as technical attributes mirroring the advantages of individual technologies. Context-specific definitions of selected criteria are shown in Table 5.3

Table 5.3 Evaluation criteria for ranking solid waste treatment technologies

Criteria	**Units**	**Category**	**Description**
Investment cost	USD	Economic	expenditure required to: 1) purchase property and fixed assets; and 2) procure initial, additional, or replacement equipment, to meet specific operational objectives of entity making the investment
Safety	Ordinal	Social	*describes the condition of* freedom from perils and injury. Exposure to health hazards may be acute or chronic.
Operational cost	USD	Economic	recurrent expenditure on fuel/power for operations, maintenance and or leasing of equipment, and other service fees, made by owner/operator of productive technical assets
Land use	ha	Environmental	exclusion area required to install and operate specific technologies
Employment	Ordinal	Social	new employment opportunities created by introduction of particular technology
Feasibility	%	Technical	reflects the probability of successfully introducing particular technologies
Versatility	Ordinal	Technical	reflects a particular technology's ability to treat solid and liquid waste streams

---

[61] In old dumpsites such as Bakoteh, some leakages are still expected to occur from lateral boundaries eve after the top layers of waste have been sealed off.

[62] https://en.wikipedia.org/wiki/Incineration

Criteria	Units	Category	Description
Secondary output yield	%	Technical	relative economic value of secondary outputs from a particular treatment process, as a measure of other benefits
Sustainability (feedstock)	Ordinal	Technical	reflects long-term viability of operations based on a particular technology, regardless of its technical feasibility
Air pollution	Ordinal	Environmental	risks of health-threatening atmospheric pollution from normal operations of a particular technology
Groundwater pollution	Ordinal	Environmental	risks of contamination of groundwater resources from normal operations of a particular technology

5.5 Results of technology prioritisation for the waste sector

Results presented in this section of the report derive from MCA procedural steps described in section 2.3. According to weighted scores and corresponding rank order of waste management technologies reported in Table 5.4, bioreactor and sanitary landfill technologies symbolise the two top prospective mitigation technologies in the Gambian waste sector.

Table 5.4 Results of multi-criteria analysis (MCA) of waste sector technology options

Option	Weighted Score	Rank
Sanitary landfill	71.8	2
Bioreactor landfill	73.0	1
Anaerobic Digester	47.1	4
Waste Incinerator	42.3	5
Aerated Static Pile (composting)	64.4	3

To test the robustness of findings reported in Table 5.4, sensitivity analyses underpinned by selective and deliberative amendments of category and individual weight of economic and environmental criteria shown in Table 5.5 were conducted. In the first of two sensitivity analyses (i.e., Run 1), the category weight assigned to environmental criteria was four times heftier than the corresponding value for economic criteria. In Run 2, category weights for environmental and economic criteria were roughly equal, whilst, technical and social criteria weights did not vary from their Base Case values in both analyses.

MCA results based on these modified criteria weights yield a complex set of results in Table 5.6 (See Annex III for detailed computations). The change in criteria weights in Run 1 is enough to trigger switching of rank orders of the top two technologies, and order of the two lowest ranked technologies in Table 5.4 (Base Case), as well. In Run 2, the assessment shows sanitary landfill as the top ranked technological option for solid waste management, whilst aerated static pile (composting) is propelled into second spot. The MCA concludes therefore by confirming bioreactor and sanitary landfill as the top two mitigation technologies for the waste sector under most conditions, with the possibility of aerated static pile (composting) outranking bioreactor landfill under certain conditions.[63]

---

[63] Scrutiny of data seems to suggest that the rating of options on exclusion zone and investment cost criteria have a very strong influence on overall scores.

Table 5.5 Changes in overall criteria weights feeding into sensitivity analysis of MCA results reported in Table 5.4 (Base Case)

		Base Case		Run 1		Run 2	
		Category weight	Individual weight	Category weight	Individual Weight	Category weight	Individual Weight
Criteria	**Category**						
Feasibility	Technical	30%	10%	30%	10%	30%	10%
Secondary output yield	Technical		5%		5%		5%
Sustainability (feedstock)	Technical		10%		10%		10%
Versatility	Technical		5%		5%		5%
Safety	Social	15%	10%	15%	10%	15%	10%
Social benefit	Social		5%		5%		5%
Investment cost	Economic	20%	10%	11%	6%	29%	14%
Operational cost	Economic		10%		5%		15%
Exclusion zone	Environmental	35%	5%	44%	8%	26%	2%
Ground water pollution	Environmental		15%		18%		12%
Air pollution	Environmental		15%		18%		12%

Table 5.6 Sensitivity analysis of MCA findings on waste sector technology options

Option	**Weighted score (table 5.4)**	**Sensitivity Analysis**	
		Run 1	**Run 2**
Sanitary landfill	71.8	82.8	80.8
Bioreactor landfill	73.0	79.0	67.0
Anaerobic Digester	47.1	43.1	51.1
Waste Incinerator	42.3	50.8	43.8
Aerated Static Pile (composting)	64.4	59.9	68.9

Chapter 6 Summary and Conclusions

Selection of TNA mitigation sectors was an administrative decision consistent with national efforts to chart a trajectory for green development and to bolster the country's image of responsible global citizenship. Indeed the energy, transport and waste sectors are among highest GHG emitting sectors, and constitute the focus of nascent mitigation policy and strategic priority actions. In this report, the author's task conceptually begins with a situation analysis that zeroes in on pressing challenges for each sector. Considering the raison d'être for the TNA however, challenges preeminently linked to the scale and trends of sectoral greenhouse gas (GHG) emissions are used to posit the inadequacy of existing technologies *vis-à-vis* emerging policies thereby triggering the discovery process of best available technologies for GHG emissions reduction in conformity with climate policy targets. To this end, a mixed group of stakeholders including lead s organisations/institutions drawn from the public, private and voluntary sectors, represented in the National Climate Change Committee (NCCC), brought together under the TNA and supported by the author, held deliberations on the subject matter so as to pool their ideas and information; filter out behavioural responses, regulatory and associative measures; synthesise and short-list technological options on which further information was to be developed in anticipation of preference ranking by multi-criteria analytical methods. In the process, stakeholders had to observe two important caveats: 1) proposed technologies for each sector needed to have a demonstrable function of GHG emissions reduction, and 2) proposed technologies needed at least three other alternatives with the same function for comparison.

In order to make transparent decisions jointly, stakeholders also collectively identified criteria sets for each sector and assigned weights to each criterion based on consensus. In sum, 21 criteria were identified across the three mitigation sectors, 10 of which were common to two or all three sectors. In general, technical criteria sets were larger than other sets by a factor of 2 to 3, but stakeholders had and used opportunities to set, in their judgment, the desired balance between social, environmental, technical and economic considerations by assigning and distributing group criteria weights accordingly. Due diligence was exercised to ensure that criteria sets had the requisite properties of effectiveness and cogency.

Alternative technology options were evaluated using the additive model of multi-attribute utility theory, implemented in the TNA with an Excel worksheet programmed for such a task. Limiting factors of the analytical tool include the maximum number of criteria it could handle, and perhaps more significantly stakeholders' use of qualitative assessment of criteria scores where quantification would have been less biased.

With the facilitation of the author, stakeholders concluded the multi-criteria analytical exercises by confirming:

1) combined cycle diesel generators and wind turbines as the top two technologies in the TNA for the electricity sub-sector of the energy sector;
2) direct fuel injection and turbocharger as the top two technologies in the TNA for the road transport sub-sector of the transport sector; and
3) bioreactor and sanitary landfill as the top two technologies in the TNA for the waste sector under most conditions, with the possibility of the bioreactor landfill being outranked by aerated static pile (composting) under certain conditions.

At first glance, some of the results that surfaced from the multi-criteria analytical exercises appear counter-intuitive, notably the strong performance of the combined cycle diesel generator (energy sector) and bioreactor landfill (waste sector), *vis-à-vis* other technology that stakeholders are more familiar. Still, it is important to note that current rankings do not stop decision-makers from including utility-scale solar PV and aerated static pile composting technologies in further technology assessments, or strategic deployment of specific technologies on different (management) scales. Although not materially affecting the final results of the MCA, the case for bridging/reducing knowledge gaps and uncertainties in GHG emissions is a compelling one that requires urgent attention.

List of References

Selected Readings

AF-MERCADOS EMI, 2013, Electricity Strategy and Action Plan. Consultancy report prepared for the Ministry of Energy, Banjul, 66p+Annexes.

Anderson, D.R, Dennis J Sweeney, Thomas A Williams, 1991. An introduction to management science: quantitative approaches to decision-making. 6th Edition, West Publishing Co., Minnesota. 866p

Beuving, E., De Jonghe, T., Goos, D., Lindhal, T., Stawiarski, A., 2004. Environmental impacts and fuel efficiency of road pavements. Industry Report, European Asphalt Pavement Association (EAPA)/Eurobitume, Brussels, 22p

Blodgett, C., Marett, D., Singh, H., Cocco, M., and Ndongsok, D., 2015. NAMA design document for rural electrification in the Gambia. Consultancy report for Ministry of Environment, Climate Change, Water Resources and Parks and Wildlife, Banjul, 87p+ Annexes

Blue Gold Solutions (BGS), 2006. Climate change stakeholder training in multi-criteria analysis. A training workshop report. NAPA Project LDL 2328 3734 46 99. Banjul, the Gambia. 63p.

Brown and Root Environmental, 1994. Environmental Management and Tourism Development Study, Consultancy Report prepared for Urban Environment Project Coordinating Unit.

Fishburn, P.C.,1966. Additivity in utility theory with respect to denumerable product sets, *Econometrica*, 34, 500 – 503

Foon, S, 2014. Mid-term valuation of the Programme for Accelerated Growth and Development (PAGE). Consultancy for Ministry of Finance and Economic Affairs, Banjul, 28p

GOTG, 2003. First National Communication under the UNFCCC. Department of State for Fisheries, Natural resources and the Environment., Banjul the Gambia., 94p

GCAA, 2015. Gambia Civil Aviation Authority 2014 Annual Report. Ministry of Works, Transport and Infrastructure, Banjul, 60p.

GOTG, 2011. Programme for Accelerated Growth and Development – 2012 to 2015. Ministry of Finance and Economic affairs, Banjul, 151p + Annexes

GOTG, 2012a. The Gambia's Second National Communication under the United Nation Convention on Climate Change Ministry of Forestry and the Environment, Banjul, 113p.

GOTG, 2012b. Nationally appropriate mitigation actions (NAMAs). Ministry of Forestry and the Environment, Banjul, 25p + Annexes

GOTG, 2015. Intended nationally Determined Contributions (to global emissions reduction). Ministry of Environment, Climate Change, Forestry, Water and Wildlife, Banjul, 24p

GPA, 2014. Gambia Ports Authority Annual report and Financial Statements for year ended 31 December 2013. Ministry of Works, transport and Infrastructure, Banjul, 69p + Annexes.

Greene, S., Akbarian, M., Josef-Ulm, F., Gregory, J., 2013. Pavement roughness and fuel consumption. MIT, Concrete Sustainability Hub. Cambridge, 17p.

GT Board, 2015. Gambia Tourism Board 2013 Annual report. Ministry of Tourism and Culture, Banjul, 61p.

IRENA, 2013. The Gambia renewable readiness assessment (RRA). Report on in-country consultations. IRENA. Abu Dhabi, 60p + Annexes

Jallow, S. B. O., 1989. Monitoring of organochlorine pesticides in the Gambia. Internal Report. Department of Water Resources. Banjul.

Janos J. Bogardi and Hans-Peter Nachtnebel (Eds.), 1993. Multicriteria Decision Analysis in Water Resources Management. UNESCO, IHP SC/.94/WS/14, Paris, 469p

Keeney R. L. and H. Raiffa, 1993. Decisions with multiple objectives: Preferences and value tradeoffs. Cambridge University Press, Cambridge, 569p.

Lahmeyer International, 2006. *Renewable Energy Master Plan for The Gambia.*

Lamour, Y, 2013. Working Paper on Low Emission Climate Resilient Development Strategies. Consultancy study carried out for UNDP/Department of Water Resources, Banjul, 91p + Annexes

Murphy, R.J., Jones, D.E., Stessel, R.I., 1995. Relationship of microbial mass and activity in biodegradation of solid waste. *Waste Management. Res. 13*, 485-497.

Powell, J., Jain, P., Kim, H., Townsend, T., and Reinhart, D., 2006. Changes in Landfill Gas Quality as a Result of Controlled Air Injection. Environ. Sci. Technol., 40, 1029-1034

NAWEC, 2015. National Electricity and Water Company Annual Report 2013. Ministry of Energy, Banjul, 48p.

NEA, 2010. Environment Report –The Gambia (SER –TG). Banjul, The Gambia, pp201.

Njie, M., 1996. The □-Option: An alternative Strategy for Environmental Quality Monitoring & Enforcement. Commentary. Department of Water Resources, Banjul, 17p.

Njie, M. (2009). Earth systems research and systematic observations in The Gambia: Current situation and future directions. Consultancy report prepared for Second National Communication Project. Banjul, The Gambia.

Njie, M., 2014. Participatory Slum Upgrading Programme (PSUP) Phase I
National Urban Profile Review. Commentary. Pro-poor Advocacy Group, Bakau Newtown, 8p.

Njie, M, 2015. Gap Analysis Study: Low emissions and resilient economy. Consultancy report contributing to the elaboration of a national climate change policy (NCCP) for Ministry of Environment, Climate Change, Wildlife, Water And Fisheries, Banjul, 36p+ Annexes

NRA 2014. National Roads Authority Management Report 2013. Ministry of Works, transport and Infrastructure, Banjul, 40p +Annexes.

Roy, B., 1985, *Méthodologie multicritère d'aide à la décision*, Economica, Paris

Ryding , S., 1992. Environmental management handbook. IOS Press, Amsterdam, 777p

Sahel Invest, 2005. National Energy Policy, Part 1. Consultancy report prepared for the Office of the President, State house, Banjul, 80p.

Sanneh, E.S., 2013. Employing systems thinking approach to integrate salient environmental issues for sustainable development in the Gambia. PhD dissertation, National Taipei University of Technology, Taipei, 155p

Thiel, C., Perujo, A., Mercier, A. 2010. Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios. Energy Policy 38, 7142–7151.

United Nations, 2008 . International Standard Industrial Classification of All Economic Activities. Department of Social and Economic affairs, Statistics Division, United Nations Publications, ST/ESA/STAT/SER.M/4/Rev.4. New York, 291p

Urquhart, P., 2016. National climate change policy of the Gambia. Consultancy report for Ministry of Environment, Climate Change, Wildlife, Water and Fisheries, Banjul, 62p+ Annexes

WAIS, 2015. National Energy Policy (2015 – 2020): The Gambia. Consultancy report prepared for the Ministry of Energy, Banjul, 56p.

Yoe, C. (2002). Trade-Off Analysis Planning and Procedures Guidebook. Prepared for Institute for Water Resources, U.S. Army Corps of Engineers. April.

Legal and Policy Instruments

National laws

Department of Physical Planning and Housing Act (1988)
Environmental (Prevention of Dumping) Act (1988)
Public Health Act 1990)
State Lands Act (1991)
Land Acquisition and Compensation Act (1991)
Forestry Act (1998)
National Environmental Management Act (1994)
Electricity Act (2005)
National Roads Authority Act (2007)
Public Health Act (2008)
Renewable Energy Act (2013)
Companies Act (2013)
Merchant Shipping Act (2013),
Marine Pollution Act (2013),
Consumer Protection Act (2014)
Water Resources Management Bill (2014)

National Regulation

Public Health Regulations, 1990
EIA Regulations (2014),

National Policies

Sanitation Policy (2009)
Energy Policy (2014)
National Climate Change Policy (2016)

International Treaties and Conventions

UN Convention on Marine Pollution, MARPOL (1973)

Convention on the development of common infrastructure for rational exploitation of water resources of River Gambia (1978)

United Nations Framework Convention on Climate Change, UNFCCC (1992)

Annex I: Technology Factsheets for selected technologies

Energy Sector Technology factsheets

Utility-scale Solar PV (flat-plate system)

Defining characteristics	Narrative
General	The photovoltaic (PV) effect[64] was first observed by Edmond Becquerel in the 19th century, but practical applications first became possible with the development of solid-state electronic devices in the 1950s. Propelled by innovations and spinoffs of the US Space Program in the 1970s, solar PV technology debuted in the world energy markets in the 1980s. For field scale applications, solar PV technologies are distinguished into two broad categories: concentrator, and flat-plate systems, the latter being deployed more widely, globally (Green, 1993; Kelly, 1993). Essentially, flat-plate systems are built around monocrystalline or polycrystalline solar cells[65] commonly referred to as modules that transform incident solar radiation into an electrical output. When connected in series, solar cells create an additive voltage to serve as the basis for running a utility-scale power plant (Firor et al., 1993). Compared to distributed solar power generation, utility-scale solar systems (USSSs) produce significantly larger economies of scale, have a high production capacity, and can be built at the optimal geographical location, not necessarily proximal to demand centres (Hernandez et al., 2014). On average, solar panels lose 0.5% of their efficiency a year resulting in a potential loss of 12% of its output performance in 25 years (Green, 1993).
Siting and land use	USSSs are sited in areas known as solar parks. Ideally, solar parks are located in brown field sites, and approval permits informed by environmental and social impact studies. Land area required for solar parks is dependent on the geographical coordinates of the site and its topographic characteristics of the site, type solar tracking configuration, efficiency of the solar modules and rated capacity of the USSS. Field experience suggests that approximately 0.8 to 5.0 hectares of land may be required to generate $1MW_{ac}$ of electricity (IFC, 2015; Pasqualetti and Miller, 1984). With respect to a fixed tilt array system, land requirements could be 10% to 40% higher for a single axis tracker and a 2-axis tracker, respectively (Ong et al. 2013). Other site selection factors include accessibility and availability of grid connections, in consonance with the systems' strategic objectives of generating electricity at competitive costs
Design (components) and Operation	A utility-scale solar system (USSSI integrates the following sub-systems: 1) collection; 2) power conversion; and 3) storage and transmission sub-systems. The collection sub-system is made up of solar modules mounted on frames inclined at an angle slightly less than the latitude of the site and facing the equator. Alternatively, module can be mounted on supports with single axis or dual axis tracking systems[66] capable of boosting modules' efficiency by 20% to 50% (Green, 1993).[67] On exposure to direct or diffuse sunlight, individual modules produce dispatchable electrical energy proportional to incident light intensity.[68] Additive voltages of modules in series strings and parallel strings are connected to the inverters are transmitted with appropriate cablings to a power inverter[69] that converts direct current input voltage into low voltage alternating current[70] at grid frequency (50 – 60 Hz).[71] The power conversion process is

---

[64] creation of voltage or electric current in a material upon exposure to light

[65] Monocrystalline cells are generally more efficient, but are also more costly

[66] tracking the apparent movement of the sun across the sky throughout the year

[67] Spacing of module arrays and tilt of fixed mounted arrays are important considerations in optimised design (Green, 1993)

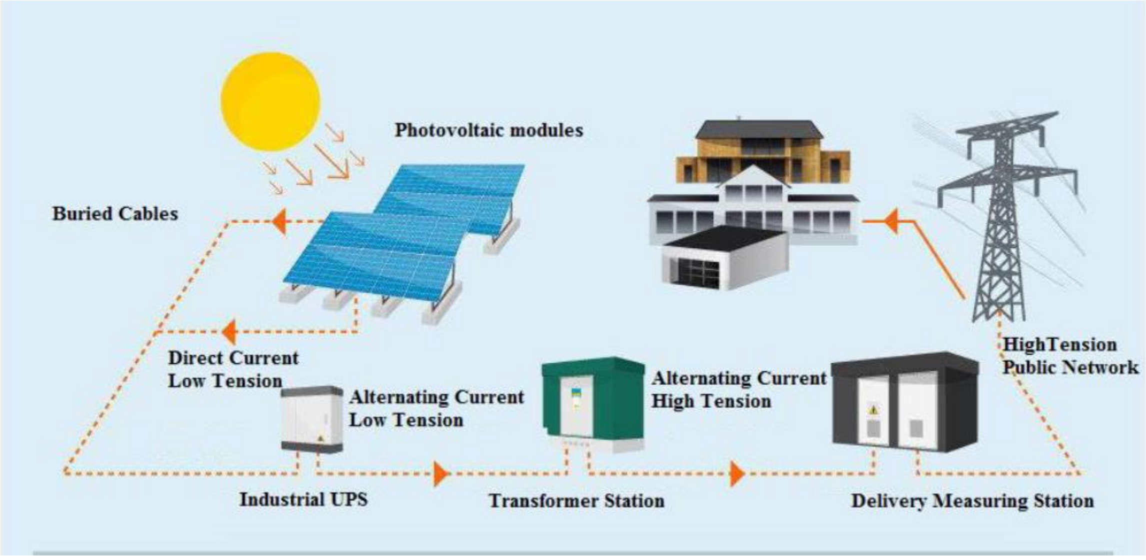
[68] Direct current components are rated to allow for thermal and voltage limits. Technical specifications of modules and guarantees are provided by manufacturers on module datasheets.

[69] In some installation, an industrial UPS serves to stabilise intermittent and rapid changes in the input voltage influenced by shading effects of passing clouds

[70] Inverters may be constructed without in-built transformers for stepping up the voltage. Inverters with transformers provide galvanic isolation but adversely affect efficiency as a result of transformer losses (IFC, 2015)

[71] The maximum number of modules in a string is constrained by the maximum direct input voltage of the inverter to which a string is connected

	completed with the aid of a (three-phase) step up transformer of known rated power that transforms low voltage alternating current (from inverter) to a high voltage output predisposed to transmission over long distances on an electric grid. On a systemic level, earthing is provided as a means to protect against electric shock, fire hazard and lightning. A delivery measuring station, typically located on the property of the electricity network operator/owner houses the required grid interface switchgear such as circuit breakers, and disconnects for protection and isolation of the USSS, as well as metering equipment (IFC, 2015, SRA International, 2008).
Costs	The cost of producing electricity using utility-scale solar PV could be highly variable, even within the same country (Sims et al., 2003). In effect, costs depend on the solar resources at the site, cost of modules and other parts of the system, cost of money, etc. Kelly (1993) and SRA International (2008) reports indicative investment costs in the order of USD0.03 to USD0.17 per kWh for sites across the US. For medium-scale projects, the author also report operation and maintenance (O&M) costs lying between USD0.03 and USD0.07 per kWh. Investment and O&M data compiled by Black and Veatch (2012) show significant economies of scale with increasing size of plant. IFC (2015) presents benchmark cost of USSS components that add up to USD1.74 million/MW_p. Crucially, modules, supporting structure and power inverter account for approximately 75% of total system costs.
Supporting infrastructure	Control room Delivery measuring station Roads Power substation
Advantages	Harvests freely available, domestic carbon-free energy resource Operates for decades with little maintenance (Kelly, 1993) More cost effective than residential scale systems (Tsuchida et al., 2015) Offers additional environmental benefits by using degraded land (Hernandez et al, 2014) Low production of hazardous wastes
Disadvantages /Challenges	Requires significant amounts of equipment and land Power produced by USSSs has fluctuations on both short and long time scales cannot eliminate the need for substantial firm power or dispatchable demand response (Curtright and Apt, 2008)
Abatement potential	Although the operation of a USSS entails no carbon emissions, emissions are non-zero from a life cycle analytical perspective. Depending on PV technologies these fall in the range of 20 - 50 gCO_2 per kWh of electricity. Still, this is far less than the carbon intensity of grid electricity reported as 500 gCO_2 per kWh (Nelson et al., 2014).
Level of penetration	USSS is a completely new technology, but there is a thriving market for solar PV, and considerable experience on small scale solar in the Gambia



Source: AfDB, 2015. Construction of the Bokhol Solar photovoltaic plant in Senegal. Project Document.

Further readings

Black and Veatch, 2012. Cost and performance data for power generation technologies. Report prepared for the National Renewable Energy Laboratory. 60p + Appendices

Curtright, A.E., Apt, J., 2008. The Character of Power Output from Utility-Scale Photovoltaic Systems. Prog. Photovolt: Res. Appl. 16:241–247.

Firor, K., Vigoth, R., Ianucci, J,J., 1993. Utility field experience with photovoltaic systems in Johanssen, T.B., Kelly, H., Reddy, A.K.N, Williams, R.H. (eds), 1993. Renewable energy: Sources for fuels and electricity. Island Press, Washington DC, pp. 482 – 512.

Green, M.A., 1993. Crystalline and polycrystalline solar cells in Johanssen, T.B., Kelly, H., Reddy, A.K.N, Williams, R.H. (eds), 1993. Renewable energy: Sources for fuels and electricity. Island Press, Washington DC, pp. 337 – 360.

Hernandez, R.R., Easter, S.B., Murphy-Mariscal, M.L., Maestre, F.T., Tavassoli, M., Allen, E.B., Barrows, C.W., Belnap, J., Ochoa-Hueso, R., Ravi, S., Allen, M.F., 2014. Environmental impacts of utility-scale solar energy. Renewable and Sustainable Energy Reviews 29, 766–779

International Finance Corporation (IFC), 2015. Utility-Scale Solar Photovoltaic Power Plants. A Project Developer's Guide. pp58-93, 173-181

Kelly, H., 1993. Introduction to photovoltaic technology in Johanssen, T.B., Kelly, H., Reddy, A.K.N, Williams, R.H. (eds), 1993. Renewable energy: Sources for fuels and electricity. Island Press, Washington DC, pp 297 – 336.

Nelson, J., Gambhir, A., Ekins-Daukes, N.,2014. Solar power for CO_2 mitigation. Grantham Institute for Climate Change, (GICC), Briefing Paper 14. Imperial College, London, 16p.

Ong, S., Campbell, C., Denholm, P., Margolis, R., Heath, G., 2013. Landr-use requirements for solar power plants in the United States. National Renewable Energy Laboratory (NREL) Technical Report. NREL/TP-6A20-56290. Available electronically at http://www.osti.gov/bridge

Pasqualetti. M.J, Miller, B.A.,1984. Land requirements for the solar and coal options. The Geography Journal. Vol.50, 2, 192 – 212.

Sims, R.E.H., Hans-Holger R., Gregory, K., 2003. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. Energy Policy 31, 1315–1326

SRA International, 2008. Solar Power Analysis and Design Specifications. Technical Manual. Environmental Protection Agency’s Brownfields Program. 23p.

Tsuchida, B., Sergici, S., Mudge, B., Gorman, W., Fox-Penner, P., Schoene, J., 2015. Comparative Generation Costs of Utility-Scale and Residential-Scale PV in Xcel Energy Colorado’s Service Area.

Websites

https://en.wikipedia.org/wiki/Photovoltaic_power_station
http://www.businessinsider.com/utility-scale-solar-is-now-comparable-to-natural-gas-2016-7

Combined Cycle Diesel Generator

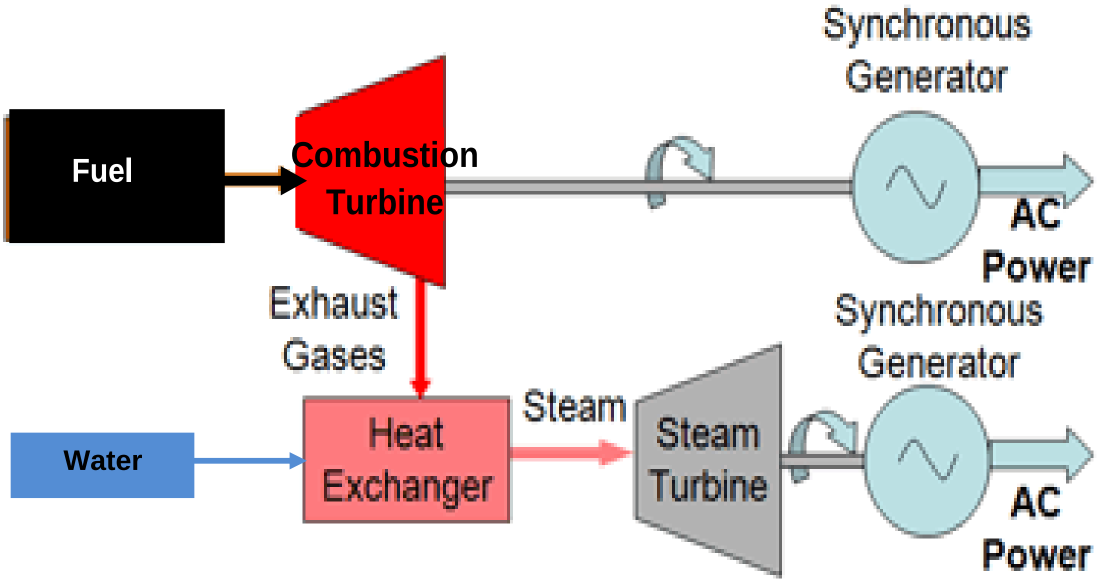
Defining characteristics	Narrative
General	A generator is a device that converts mechanical energy to electrical energy based on the principle of electromagnetic induction. Combined cycle power generation reflects a power optimisation strategy built on converting waste heat from a conventional thermal generator to dispatchable electricity by means of a parallel generating unit. To this effect, a combined cycle diesel plant integrates power production from a diesel generator and steam turbine connected to alternators that produce a synchronised alternating current output from motive forces generated by the diesel engine and steam turbine operating as distinct units. It is perhaps worth noting that the key technical components of this combined cycle power plant (CCPP) were independently developed in the 19th Century, and significantly improved over time through advances in materials science and industrial engineering. Modern generators are designed to operate in a wide range of temperature conditions (IMIA Working Group, 2015).
Siting and land use	Locational decisions concerning implantation of power stations require consideration of multiple qualitative and quantitative economic, technological, environmental and social criteria. Ideally, the site chosen for installation of a combined cycle diesel plant should not cause environmental impacts including disruption of ecosystems on contiguous land in breach of established in legal statues or industry standards. Social costs and acceptability should also be considered and discussed with communities living in close proximity to sites identified for implanting a new CCPP. Alternative land uses forecast over the life span of the plant could be equally important. As a general rule, a combined cycle diesel power plant should be located on land dedicated to medium-size and heavy industries. Using coal-fired power plant as a surrogate, combined cycle diesel power plants may require on average 0.2 ha per MW of electricity generated (Fhenakis and Kim, 2009), plus an additional 0.68 ha per MW electricity for balance of station systems (Pasqualetti and Miller, 1984).
Design (components) and Operation	A CCPP consists of two modular generation sub-systems; one of them converting chemical energy to electricity, and the other, converting thermal energy to electricity. The first sub-system represents a combustion turbine, and the second, a steam turbine, connected to one or separate alternators (IMIA Working Group, 2015).. A combustion turbine is made up of the following key components: 1) diesel engine, and 2) alternator. The major components of the diesel engine are its air intake and exhaust systems, fuel injection system, cylinder mounting, crankshaft, and camshaft. The operation cycle of a diesel engine starts with filtered air being drawn into engine cylinders, then getting heated as a result of compression by controlled movement of pistons inside the cylinder, and causing a calibrated and scheduled amount of fuel injected into the cylinder to ignite spontaneously, creating an explosive force that drives the piston to its lowest position allowing spent gases out of cylinder through exhaust valves. Diesel engines in power plants typically have 6 to 16 cylinders and the force exerted on pistons are transmitted through a crankshaft that attaches to the axis of an alternator that produces an alternating current proportional to the rotational speed of the crankshaft. The steam turbine sub-system derives its energy source from spent/flue gases produced from combustion of fuel oil in diesel engine cylinders. In a first step, exhaust gases are piped through a heat exchanger/boiler system inside which hot flue gases generate superheated steam in an elaborate network of tubes containing water containing water without the two fluids mixing. When high pressure steam flowing through connector pipes from storage drums is directed at rotor blades of the steam turbine, the pressure exerted on rotor blades causes the turbine shaft to rotate and generate electrical energy when connected to an alternator. Condensers are used to liquefy steam from the turbine

	outlet. Water is subsequently re-circulated to the heat exchanger/boiler system. In line with environmental regulations, CO, SO_2 and other pollutants are removed from flue gases before release through stacks. An alternator or synchronous generator has two major components: 1) a rotor, and 2) armature coils. In general, armature coils are stationary whilst the rotor, driven by a prime mover, rotates and produces a changing magnetic field around the armature inducing an alternating current in the armature coils, in the process.[72] Key variables of the alternating current generated such as voltage and frequency are related to the strength of the magnetic field, armature design and rotor speed. Transformers boost voltage output up to 400,000 volts to facilitate transmission over the grid.
Costs	Investment and operating costs for combined cycle diesel power plants depend on a multitude of variables including rated power output of plant, its technical configuration, fuel costs, flue gas cleaning technology, and balance of station systems. That said, cost information relating to small scale CCPPs is sparse. Investment costs range from USD676/kW for a conventional combustion turbine (85MW) to USD1,023/kW for an advanced CCGT plant (400MW), with corresponding fixed operation and maintenance (O&M) costs of USD7.04/kW.yr and USD13.17/kW.yr, respectively (SAIC, 2013), not discounting regional cost adjustments (SAIC, 2013). Over long distances, or in larger countries, or even smaller ones with contrasting landscape, geographical differences in price of specific project inputs could be significant (Njie, 2008; Mouyelo-Katoula and Nshimyumuremyi, 2007).
Supporting infrastructure	Roads Power house (sound-attenuated enclosure, control room, internal switchgear room) Office Workshops and storage External switchgear room Tank farm (storage and buffer tanks, perimeter bunds) Purifier and pumphouse Fire protection system Pipework and cable connections Transformer
Advantages	High load bearing capacity Can accommodate base load, peaking, emergency or standby power applications (Aabakken, 2006) Highly reliable Moderate O&M costs Can achieve 50%-200% gains in efficiency relative to setup with conventional combustion turbine (IMIA Working Group, 2015) Does not require much land as renewable energy conversion technologies (Fhenakis and Kim, 2009
Disadvantages /Challenges	Atmospheric emissions (CO_2, SO_x, NO_x) Land and water pollution (wet deposition) Occupational health hazards Noise pollution Hazardous waste residues
Abatement potential	Uncertainties surrounding abatement potential of a combined cycle diesel power plant rests on efficiency gains and quality of fuel used in its combustion turbine. Assuming plant efficiency gains of 50 to 200% (IMIA Working Group, 2015) on a fuel with specific carbon dioxide emission lying between values associated fuel oil and lignite, a combined cycle diesel power plant can be expected to offset between 0.0731gCO_2/kWh and 0.31gCO_2/kWh of electricity produced.

---

[72] Based on Faraday's law of electromagnetic induction

Level of penetration	The Gambian public utility company, NAWEC operates one generator working on same principles



Adapted from: https://www.google.gm/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwiawvPi7ZnQAhVD2hoKHdLpDvoQjRwIBw&url=http%3A%2F%2Fwww.mpoweruk.com%2Fhybrid_power.htm&bvm=bv.138169073,d.d2s&psig=AFQjCNHG4LL1qOXLUWzGjVNZ9HxrmsnsFA&ust=1478718474077983

Further readings

Aabakken, J., 2006. Power Technologies Energy Data Book. *Technical Report.* NREL/TP-620-39728

Fthenakis, V., Kim, H.C., 2009. Land use and electricity generation: A life-cycle analysis. Renewable and Sustainable Energy Reviews 13, 1465–1474

IMIA Working Group, 2015. Combined Cycle Power Plants. IMIA Working Group Paper 91 (15) IMIA Annual Conference 2015, Merida (Yucatán), Mexico 26-30 September 2015

Mouyelo-Katoula, M., Nshimyumuremyi, A., 2007. Construction and Civil Engineering Work: Designing a Time-Space Index. The African Statistical Journal, Vol. 4, May 2007.

Njie, M., 2008. Costing Priority Adaptations: A View from NAPAs. Paper presented at Experts Workshop on Economics of Adaptation, OECD, Paris, April 7 and 8, 2008.

Pasqualetti. M.J, Miller, B.A.,1984. Land requirements for the solar and coal options. The Geography Journal. Vol.50, 2, 192 – 212.

SAIC, 2013. Updated capital cost estimates for utility-scale electricity generating plants. Technology Documentation Report. Prepared for USEIA. 145p + Appendices.

Websites

http://www.dieselserviceandsupply.com/Cogeneration_Technology.aspx
https://www.youtube.com/watch?v=MulWTBx3szc
https://www.youtube.com/watch?v=c7g88IiIu5A
https://en.wikipedia.org/wiki/Combined_cycle
https://powergen.gepower.com/resources/knowledge-base/combined-cycle-power-plant-how-it-works.html

Wind Turbine

Defining characteristics	Narrative
General	Wind energy has been harnessed in different forms by ancient civilisations, and domesticated for the past two millennia through simple windmills employed to pump water and grind grain in China, the Middle East and Europe. Similar to windmills, modern wind turbines extract energy from the ambient wind field, but go a step further in transforming mechanical energy of rotation into electricity. Wind turbines come in different sizes and configurations, but exist practically in two generic forms: vertical axis wind turbines (VAWT)), and horizontal axis wind turbine (HAWT); individually defined from the orientation of a turbine's axis relative to the direction of the windstream striking the turbine. Although VAWT has demonstrable advantages under certain conditions, the use of HAWT for energy production is more is more widespread (Cavallo et al, 1993). As trend to towards carbon-free renewable technologies pick up pace, integration of power production from large numbers of wind turbines is becoming an attractive option for policy-makers and investors.
Siting and land use	Large numbers of wind turbines operating in an integrated mode are sited in areas commonly referred to as wind farms. First and foremost, wind farms are located in areas with high wind resources potential. In addition, wind farms also tend to be associated with higher topography, and landscapes relatively free of natural and engineered structures generating or increasing wind turbulence. Land area required to establish wind farms is ultimately dependent on wind energy potential of proposed sites, and rated capacity of turbines. According to Fhenakis and Kim (2009), total land use varies between 6.5 and 19 ha/MW. However only 1 – 10% of wind farms are directly use, and the remaining area is available for other land uses such as farming and animal grazing (Fhenakis and Kim, 2009; Cavallo et al, 1993). In the case of off-shore wind farms, key considerations include existing uses, alternative uses, accessibility, bathymetry and geology of potential sites.
Design (components) and Operation	Modern wind turbines are designed to safely harvest kinetic energy from wind streams characterised by high temporal and spatial variability, and comprise in essence of five basic components: 1) tower; 2) rotor; 3) yaw system; 4) drive train; and 5) electric and electronic systems. A nacelle which houses the drive train and power systems, tower and rotor are the most recognisable parts of the turbine. A single tower made up of bolted steel sections, approximately the rotor diameter in height, tapering from the bottom upwards supports the turbine rotors, nacelle and yaw mechanism. The hollow steel sections making up the tower also accommodate an access ladder, power cables, and power controls and transformer in some installations. Aerodynamic in shape, and usually consisting of three blades,[73] the rotor is attached to a steel hub. Rotor movement is actuated by incident wind flow within design speeds of operation. Start-up velocities define the lower wind speed threshold at which the turbine operates. At high wind velocities, generally above 25 m/s, variable pitch blades provide aerodynamic braking to protect the turbine from damage.[74] Working from another design perspective, fixed pitched blades induce flow separation of at the surface of rotor blades in high wind conditions, and are also equipped with tip brakes to help bring the rotor to a complete stop. A blade tilting mechanism ensures that rotor blades are exposed to the windstream at an optimum angle (Cavallo et al., 1993). Thus, rotor movement converts the wind's linear kinetic energy into rotational kinetic energy transmitted and amplified through a drivetrain to the generator. Within the drivetrain, a system of gears increases the angular velocity of the rotor to an

---

[73] Most rotor blades in use today are built from glass fiber-reinforced-plastic.

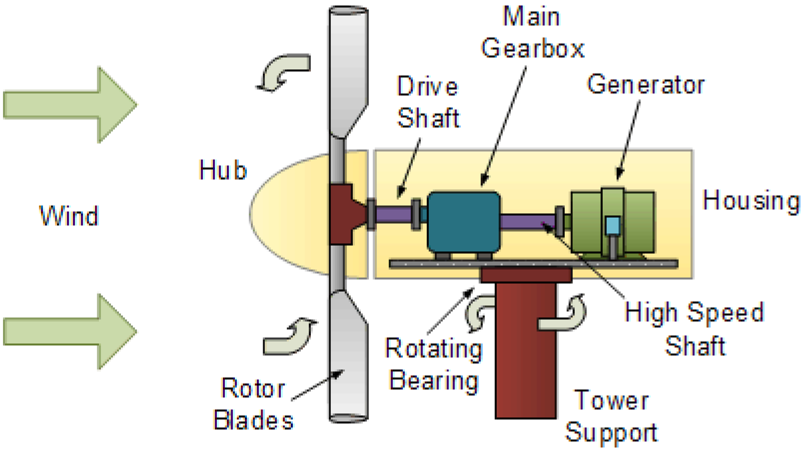
[74] A rotor with variable pitch blades can also be more efficient in terms of power production over a wide range of wind speeds.

	output shaft with rotational speed sufficient to produce power at 50 to 60 Hz from the generator. A mechanical breaking system is also used as required to preserve the integrity of the turbine. Modern wind turbines have synchronous generators which consist of two basic elements; armature coils and rotor coils. Whereas armature coils remain stationary, rotor coils, connected to the spinning transmission shaft in the drive train, produce a changing magnetic field that induces electricity in the armature coils.[75] Maximum power output is attained when rotor angular velocity is locked to the line frequency (i.e., utility grid frequency), but decoupling rotor angular velocity has several advantages including increased annual energy output[76] (Cavallo et al., 1993). A cooling fan is installed at back of the nacelle to ensure dissipation of waste heat from generator. A nacelle-based or ground-based transformer boost voltage output to facilitate transmission over the grid. A wind speed and direction sensor on top of the nacelle continuously monitors variations in the wind field, and sends a signal to yaw motors that serve to re-align the rotor axis with the prevailing wind direction.
Costs	Costs of wind turbine are strongly correlated with technical specifications of the system and also balance of system costs. Furthermore, costs are modulated by locational and scale effects as well as trends in the energy markets (Fingersh et al. 2006; Cavallo et al., 1993). In this regard, SAIC (2013) report investment costs in the range of USD2,213/kW for an onshore turbine (100MW) to USD6,230/kW for an offshore turbine (400MW), with corresponding fixed operation and maintenance (O&M) costs of USD39.55/kW.yr and USD74.00/kW.yr, respectively. Black and Veatch (2012) report comparable capital cost of USD1,980/kW but significantly lower estimates of fixed O&M cost for onshore turbines. In addition, Black and Veatch (2012) reports investment cost of USD3,310/kW and USD4,200/kW for fixed-bottom and floating-platform offshore wind turbines, respectively, noting the existence of fewer studies pertaining to the latter.
Supporting infrastructure	For onshore turbines: Roads Electrical interface connections Power substation For offshore systems (additionally): Underwater collection system Service vessels Port and staging equipment
Advantages	Harvests freely available, domestic carbon-free energy resource One of lowest priced renewable energy technologies (SAIC, 2013) Small land foot print (Fhenakis and Kim, 2009) Mostly preserves existing land use (Cavallo et al, 1993)
Disadvantages /Challenges	Requires higher initial investments than conventional combustion turbines Power generation tracks fluctuating wind regime Noise pollution Risk of catastrophic loss when braking mechanisms fail
Abatement potential	CO_2 emissions abatement as a consequence of wind turbine deployment depends not only on the fuel mix powering the grid, but also on the performance characteristics of turbine technology variants. From a fuel substitution approach, wind turbines could reduce emissions by 434 to 975 gCO_2 per kWh of electricity produced from natural gas and coal-fired turbines respectively (White, 2004)
Level of penetration	Low

---

[75] Based on Faraday's law of electromagnetic induction

[76] It is worth noting that these gains are associated with additional investments in power handling electronics



Source:
https://www.google.gm/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwjTksbpw5vQAhWFnRoKHTItBxsQjRwIBw&url=http%3A%2F%2Fwww.alternative-energy-tutorials.com%2Fwind-energy%2Fwind-turbine-design.html&bvm=bv.138169073,d.d24&psig=AFQjCNFaU2NJzR5Zv7FCpT_sky5Zhwtevw&ust=1478775940925025

Source:
https://www.google.gm/imgres?imgurl=https%3A%2F%2Fs-media-cache-ak0.pinimg.com%2Foriginals%2F0e%2F66%2F40%2F0e6640238a65f23a3033c1ad92757fb9.jpg&imgrefurl=https%3A%2F%2Fwww.pinterest.com%2Fwindturbinehome%2Fwind-generator-kitsets%2F&docid=e0C4bbh0sCzKdM&tbnid=HHX-n-RkBbwCMM%3A&vet=1&w=1024&h=768&bih=662&biw=1366&ved=0ahUKEwjHntbJxJvQAhUCRhQKHf-BCgw4ZBAzCEYoRDBE&iact=mrc&uact=8

Further Reading

Black and Veatch, 2012. Cost and performance data for power generation technologies. Report prepared for the National Renewable Energy Laboratory. 60p + Appendices

Cavallo, AJ., Hock, SM., Smith, DR., 1993. Wind energy technology and economics in Johanssen, T.B., Kelly, H., Reddy, A.K.N, Williams, R.H. (eds), 1993. Renewable energy: Sources for fuels and electricity. Island Press, Washington DC, pp. 121 - 156.

Fingersh, L., Hand, M., Laxson, A., 2006. Wind turbine design, cost and scaling Model. *Technical Report.* NREL/TP-500-40566

Fthenakis, V., Kim, H.C., 2009. Land use and electricity generation: A life-cycle analysis. Renewable and Sustainable Energy Reviews 13, 1465–1474

SAIC, 2013. Updated capital cost estimates for utility-scale electricity generating plants. Technology Documentation Report. Prepared for USEIA. 145p + Appendices.

White, D., 2004. Reduction of carbon dioxide emissions: estimating the potential contribution from wind-power. Report Commissioned and published by the Renewable Energy Foundation. London, 37p.

Websites

https://en.wikipedia.org/wiki/Wind_turbine
http://energy.gov/eere/wind/advantages-and-challenges-wind-energy

Tidal Stream Generator

Defining characteristics	Narrative
General	Tidal streams are water currents associated with the periodic piling up and ebb of water masses in oceans, coastal seas and estuaries driven by gravitational interaction between the Earth and the Moon. Tidal streams are thus characterised by continuous changes in speed and direction, and are usually stronger nearer to the coast. Historically, the global oil crisis in the 1970s and global environmental and energy policies in subsequent decades are two of the key driving forces behind invigorated interest in tidal energy resources, whose viability was first demonstrated by the commissioning of the Rance tidal power station in 1966.[77] Essentially, tidal stream power generation is a non-barrage approach to power generation that uses axial turbines, oscillating hydrofoils, Archimedes screws, and Venturi devices to extract energy from the mass of moving water. Axial turbines, the most commonly deployed tidal stream generators (TSGs) technology harvest kinetic energy of water mass in much the same way as a wind turbine does from windstreams. Prototype and commercial TSG installations can be found in the UK, Norway and US (Hammons, 2011; Khan et al., 2009; Meisen and Loiseau, 2009; Bahaj and Myers, 2003).
Siting and land use	Selecting an appropriate location for TSGs is one of the most important aspects of filed deployment of the technology. Siting is ordinarily preceded by extensive field surveys and informed by knowledge of areas with fast currents. Other key considerations include existing uses, alternative uses, accessibility, bathymetry and geology of potential sites. Some TSGs can even be attached to existing infrastructure such as bridges if these are optimally located from an energy production perspective. In all instances, permits must be obtained prior to deployment, with impacts on navigation, fishing and marine life being three critical decision factors. The size of a tidal farm, that is, the area required for installation of large numbers of TSGs, ultimately depends on the tidal energy potential of the site, and rated capacity of turbines.
Design (components) and Operation	Horizontal axis flow TSGs are made up basically of four basic parts: 1) a mooring system, 2) rotor, 3) gearbox, and 4) an electrical generator. A low speed shaft connected to rotor, gearbox and electrical generator r are housed inside a water-tight nacelle that connects to a power transmission cable. Some TSG designs include a yaw mechanism that rotates the nacelle into the tidal current thus augmenting efficiency of the TSG. In some other designs, rotors' direction of rotation reverses with in reaction to a reversal of the direction of tidal streams whilst the nacelle remains stationary (Meisen and Loiseau, 2009; Bahaj and Myers, 2003) Variable pitch rotor blades, two or three in number, 6 to 25 meters in diameter, partially harvests the kinetic energy as water flows through their sweep area. The angular velocity of rotating blades is increased several-fold in a gearbox that connects to an alternator generating an alternating current based on the principle of electromagnetic induction.[78] Generated electricity[79] is delivered to a collection system on sea floor supplies power via a submarine cable to an on-shore sub-station where the voltage is stepped up before it is sent into the grid. TSGs are stably maintained the mass of flowing water on structural support elements that form the basis of a mooring system. The less common surface-based mooring systems consist primarily of a rigid support shaft protruding from a pontoon into the water below. Sea floor mooring systems include sunken piles, concrete blocks and tripod trusses. Crucially a turbine and mooring system have to resist axial thrust to avoid catastrophic dislocation (Khan et al., 2009; Bahaj and Myers, 2003). Piles usually

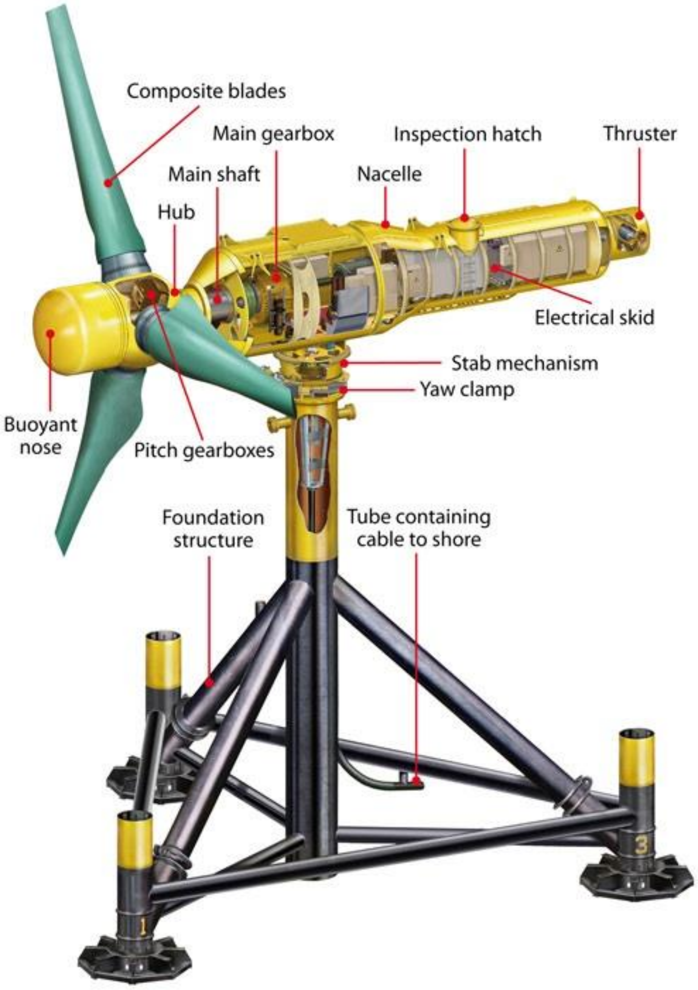
---

[77] On the estuary of the Rance River in Brittany, France

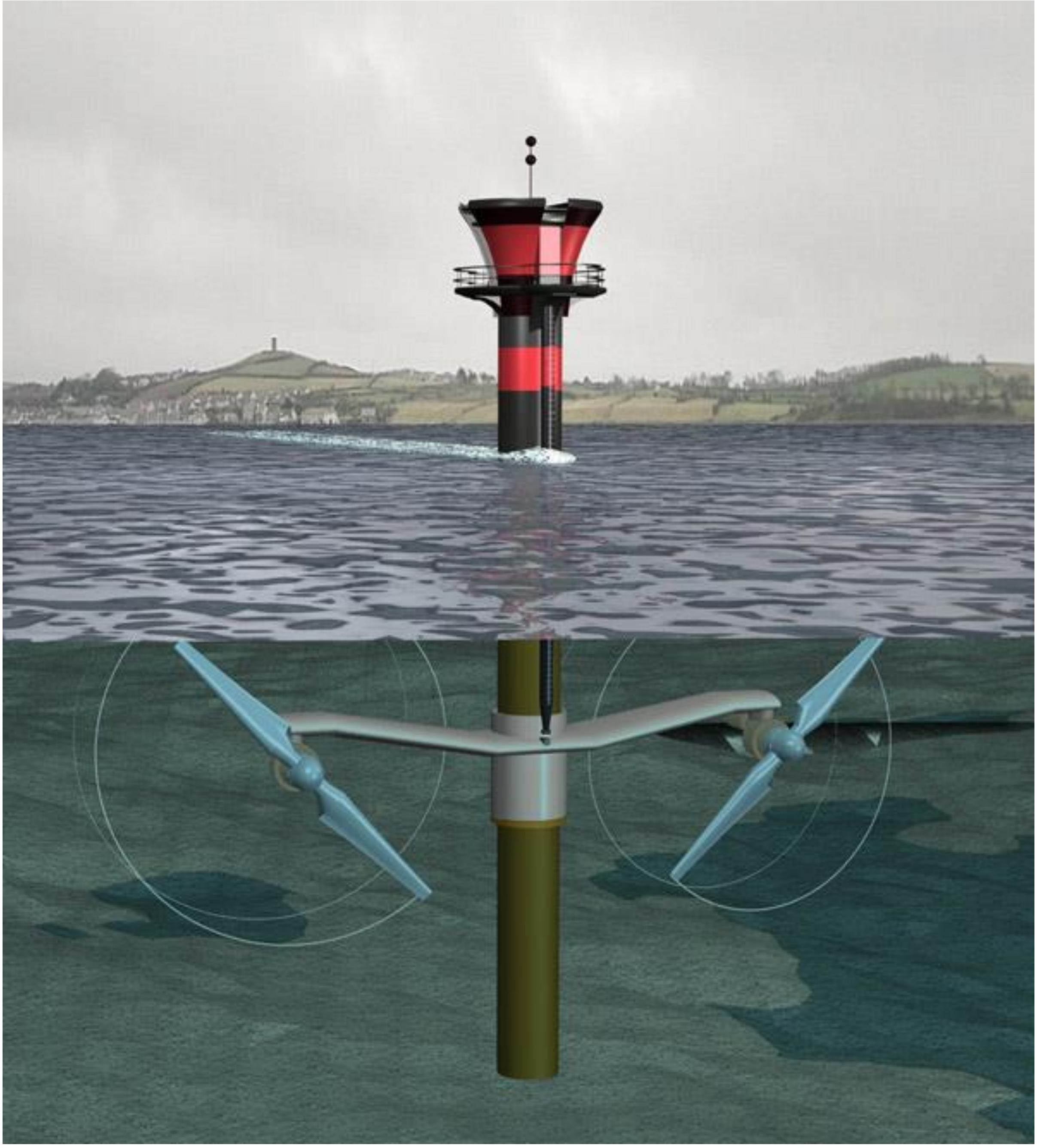
[78] Faraday's law of electromagnetic induction

[79] In the range of 300 to 1200 kW per turbine currently

	rise above the water surface, and in some configurations can accommodate multiple turbines. For cost-effective and efficient power production, an array of TSGs may be needed and this also calls for careful design in order to curtail efficiency losses due to wake effects generated by individual devices. A single row of TSGs is likely to be the most efficient configuration; good location decisions hold the key to efficient energy capture.
Costs	As with most renewable energy technologies, location-specific energy density of the energy resources has a big impact on unit costs of energy production. In the UK, reputed to have some of the world's most promising tidal stream sites, capital cost of electricity generation from TSG deployment is estimated to lie between GBP1429/kW and GBP1,736/kW (Hammons, 2011). Elsewhere in the US, capital cost is estimated at USD5,880/kW, with corresponding fixed operation and maintenance (O&M) cost of USD198/kW.yr (Black and Veatch, 2012).
Supporting infrastructure	Transformer Control room Service vessel A facility for raising the turbine unit
Advantages	Can typically produce four times the energy generated per rotor sweep as an equally power-rated wind turbine (Meisen and Loiseau, 2009). High load factors and predictable resource characteristics (Bahaj and Myers, 2003) Little environmental impact
Disadvantages /Challenges	Technology still undergoing development (Khan et al., 2009 Costly installation and maintenance (Black and Veatch, 2012) Hazards to large sea mammals, navigation and shipping Risks of fouling from growth of marine organisms on the blades and mechanism (increasing drag and hence reducing performance)
Abatement potential	CO_2 emissions abatement as a consequence of tidal stream turbine deployment depends not only on the fuel mix powering the grid, but also on the performance characteristics of turbine technology variants and their operating environment. In analogy to wind turbines, tidal stream turbines could reduce emissions by 434 to 975 gCO_2 per kWh of electricity produced from natural gas and coal-fired turbines respectively.
Level of penetration	TSG is an emerging technology, completely new to the Gambia



Source:
https://www.google.gm/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwjKudmiyJvQAhXLzRoKHTzsBM0QjRwIBw&url=https%3A%2F%2Fwww.pinterest.com%2Fsusanabaston%2Fmarine-renewables%2F&psig=AFQjCNHEHbahtPVQmgG5VkZNPbtiFuC_3g&ust=1478776943755967



Source:
https://www.google.gm/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwja4dSoyZvQAhVM2BoKHb2PDCAQjRwIBw&url=http%3A%2F%2Fwww.esru.strath.ac.uk%2FEandE%2FWeb_sites%2F10-11%2FTidal%2Ftidal.html&psig=AFQjCNHEHbahtPVQmgG5VkZNPbtiFuC_3g&ust=1478776943755967

Further readings

Bahaj, AS., Myers, LE., 2003. Fundamentals applicable to the utilisation of marine current turbines for energy production. Renewable Energy 28 (2003) 2205–2211

Black and Veatch, 2012. Cost and performance data for power generation technologies. Report prepared for the National Renewable Energy Laboratory. 60p + Appendices

Hammons, T., 2011. Tidal Power in the UK and Worldwide to Reduce Greenhouse Gas Emissions. international Journal of Engineering Business Management. Vol. 3, No. 2, pp 16-28.

Khan, M.J., Bhuyan, G., Iqbal, M.T., Quaicoe, J.E., 2009. Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. Applied Energy, 86, 1823–1835.

Meisen, P., Loiseau, A., 2009. Ocean energy technologies for renewable energy generation. Monograph. Global Energy Network Institute (GENI). Paris, 27p.

White, D., 2004. Reduction of carbon dioxide emissions: estimating the potential contribution from wind-power. Report Commissioned and published by the Renewable Energy Foundation. London, 37p.

Websites

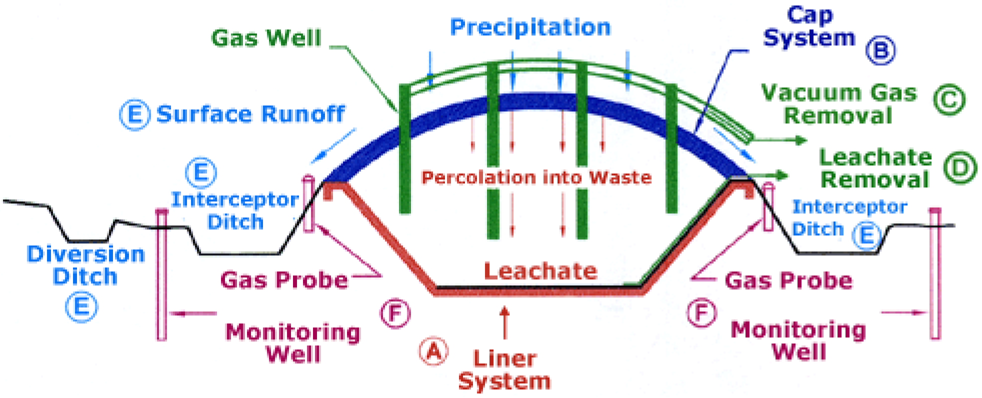
http://www.alternative-energy-tutorials.com/tidal-energy/tidal-stream.html
https://www.theguardian.com/uk-news/2016/sep/12/worlds-first-large-scale-tidal-energy-farm-launches-scotland

Waste Sector Technology factsheets

Sanitary landfill

Defining characteristics	Narrative
General	Historically, landfills have been the most common method of waste disposal and remain so in many places around the world today. In particular, sand and gravel pits and borrow areas are commonly used as primitive landfills. Sanitary landfills get their name from health-focused improvements in design and facility management compared to open dumps. Improved designs include the emplacement of materials and structures to contain the release of contaminants into the environment, and soil covering to address odour issues and curtail insect and vermin infestation of the site. In some cases, methane generation is encouraged, and the gas thereby generated collected and used as fuel. A properly designed and well-managed landfill can be a hygienic and relatively inexpensive method of disposing of waste especially in countries that have adequate land resources to accommodate these sites.
Siting and land use	Landfill siting requires rigorous geotechnical, environmental and economic studies to ensure that the best available science is used and local environmental and safety concerns are taken into account. In this regard, a facility location decision must be informed by expertise in diverse areas and stakeholder/public consultations, and validated through a permitting process. Ultimately, land requirements for installation of a sanitary landfill depend on its design life span, topography and hydrogeology of the milieu.
Design (components) and Operation	After solid waste has been tipped by trucks into a landfill, bulldozers are used to spread and compact the waste in order to utilise available landfill capacity to the fullest. Daily waste deposits are then covered with soil to reduce odours and provide a firm base upon which vehicles may operate. The use of daily cover may preempt the occurrence of landfill fires, and limit adverse visual impact. Under anaerobic conditions prevalent in landfill sites, the biodegradable fraction of solid (and semi-liquid/liquefied) waste is broken down by micro-organisms into intermediate organic compounds and finally into landfill gas (LFG), principally made up of methane and (CH_4) and carbon dioxide (CO_2), and water (Barlaz et al. 1989). Seepage from landfills, commonly referred to as leachate, is controlled by the hydroclimatic conditions at the landfill site, hydraulic properties of the landfill and biological and chemical processes taking place within the landfill. In modern sanitary landfills, the waste is isolated from the ground water by a liner system, and from flooding by surface drainage structures. Key sanitary landfill components are as follows: 1) stormwater management system; 2) landfill liner; 3) leachate collection system; and 4) gas collection and recovery system. Stormwater control systems play a crucial role diverting surface runoff from the landfill and protecting it from flooding. Typical infrastructure includes detention basins, diversion berms and cutoff ditches. A landfill liner made of a low conductivity natural or synthetic material (compacted clay or geotextile) is laid out at the bottom of the landfill to prevent or delay the migration of leachate (loaded with micro-organisms, organic and inorganic contaminants) into underlying aquifers and nearby surface water bodies. A typical leachate collection system is made up of hydraulically connected drainage material, leachate collection pipes, riser pipes and submersible pump that collectively function to remove leachate impeded by the liner at the base of the landfill. Failure to control leachate build-up and its removal will most likely cause seepage from the sides and slope instability. A gas collection and recovery system makes it possible for gas generated from waste through biochemical reactions to be pumped out of the landfill to prevent spontaneous fires, gas migration onto adjacent properties, and for use as an energy resource if desirable. A typical set-up includes one or more vertical/horizontal

	wells strategically positioned within the landfill, a header system to connect gas collection wells to a gas pumphouse system. To purify landfill gas (LFG) for end users, carbon dioxide (CO_2) can be removed by dissolving in water or potassium hydroxide (KOH). In the event LFG is not needed, it can be oxidised using a flare system (Hirshfeld et al .1992, Humer and Lechner, 1999).
Costs	The construction and operating cost of sanitary landfills depends on a multitude of locational factors, design features, equipment deployed, volume and type of wastes disposed, maintenance costs, wage and salary costs of personnel, etc. Thus, a detailed engineering study and cost estimate is an absolute necessity for each individual landfill site. To this effect, To fix some ideas, Clayton and Huie (1900) provide annual solid waste disposal costs in excess of USD1.9/ton for facilities handling 100 tons of waste or less in a day. In the authors' worked example, costs decrease exponentially to around USD0.65/ton for facilities receiving 1,200 tons of waste or higher in a day.
Supporting infrastructure	Vehicle wheel cleaning facilities Leachate treatment and disposal plant/facility
Advantages	Sanitary landfills provide a means for significant reduction of adverse environmental impacts, nuisance factors and health risks associated with primitive dumpsites. Methane, a potent greenhouse gas, can be safely captured and oxidised or utilised as a primary source of energy.
Disadvantages /Challenges	Design challenges relate to maintaining the conveyance efficiency of the leachate collection system over landfill's active life (i.e. several decades/centuries) in the face of continual clogging by silt, mineral encrustation or micro-organism growth in the pipes. Additionally, infrastructure materials should be able to survive in hostile environments and able to withstand the crushing weight of overlying garbage. Precautionary measures include the use of steep pipe grades, high density polyethylene (HDPE) pipework, and condensation traps to overcome potential problems highlighted.
Abatement potential	LFG generation is not only highly dependent on design and operational factors, but also on waste composition. Notwithstanding the high variability of landfill LFG generation (Oonk and Boom, 1995; Lou and Nair, 2009), LFG capture and flaring (i.e., conversion of CH_4 to CO_2) reduces the global warming potential (GWP) of landfill emissions by 95%. Under field conditions, the scope of GHG emissions abatement is tributary to the efficiency of LFG recovery, reported to be between 50% and 100% (Pipatti and Wihersaari, 1998), whilst Lou and Nair (2009) found lower floor and ceiling efficiency figures of 24% and 60%, respectively.
Level of penetration	Sanitary landfills are a completely new technology



Source:
https://www.google.gm/imgres?imgurl=http%3A%2F%2Fwww.pawasteindustries.org%2Fresource%2Fimage%2Fschematic2.gif&imgrefurl=http%3A%2F%2Fwww.pawasteindustries.org%2Fenvironm

ent%2Fdesign&docid=-7pld9uIGdJdlM&tbnid=QUe6LJSsA9ptHM%3A&w=500&h=214&bih=662&biw=1366&ved=0ahUKEwjQh46v7PjPAhXJORoKHdswA-0QMwh4KD0wPQ&iact=mrc&uact=8

Further Reading

Barlaz, M.A., Schaeffer, D.M. and Ham R.K., 1989. Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill. Applied and Environmental Microbiology, Jan. 1989, p. 55-65

Hirshfeld, S, Vesilind, P.A,, Pas. E.I., 1992. Assessing the true cost of landfills. Waste Management and Research, 10, 471-484.

Humer, M., Lechner, P., 1999. Methane oxidation in compost cover layers on landfills. Proceedings of the Seventh International Waste Management and Landfill Symposium 3, 403–410.

Lou, X.F. and Nair, J. The impact of landfilling and composting on greenhouse gas emissions – A review. Bioresource Technology 100, 3792–3798

Oonk, J., and Boom, A., 1995. Landfill gas formation, recovery and emissions. In: Pipatti, R., Wihersaari, M., 1998. Cost-effectiveness of alternative strategies in mitigating the greenhouse impact of waste management in three communities of different size. Mitigation and Adaptation Strategies for Global Change 2, 337–358.

Pipatti, R. and Wihersaari, M. 1998. Cost-effectiveness of alternative strategies in mitigating the greenhouse impact of waste management in three communities of different size. Mitigation and Adaptation Strategies for Global Change 2, 337–358.

Websites

https://en.wikipedia.org/wiki/Landfill

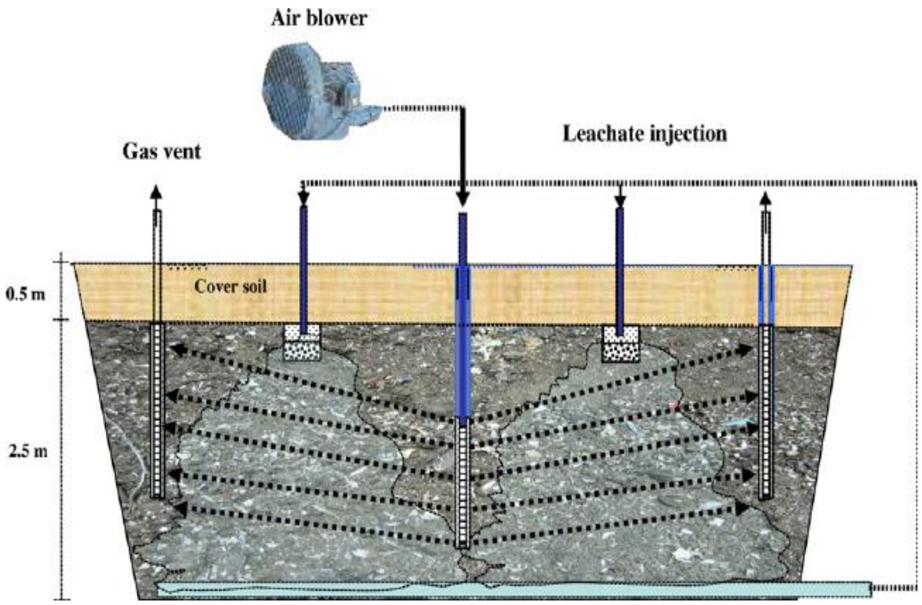
Bioreactor landfill

Defining characteristics	Narrative
General	Historically, landfills have been the most common method of waste disposal and remain so in many places around the world today. In particular, sand and gravel pits and borrow areas are commonly used as primitive landfills. A bioreactor landfill changes the goal of landfilling from waste storage to waste treatment (Pacey et al, Undated). In addition to improved design of sanitary landfill features, bioreactor landfill designs incorporate a leachate recirculation system that augments waste decomposition kinetics, and accelerates landfill stabilisation.
Siting and land use	Landfill siting requires rigorous geotechnical, environmental and economic studies to ensure that the best available science is used and local environmental and safety concerns are taken into account. In this regard, a facility location decision must be informed by expertise in diverse areas and stakeholder/public consultations, and validated through a permitting process. Ultimately, land requirements for installation of a bioreactor landfill depend on its design life span, topography and hydrogeology of the milieu.
Design (components) and Operation	Bioreactor landfills have common features with sanitary landfills as follows: 1) stormwater management system; 2) landfill liner; 3) leachate collection system; and 4) gas collection and recovery system, and two other distinguishing features; 5) leachate recirculation system; and air injection system. Stormwater control systems play a crucial role diverting surface runoff from the landfill and protecting it from flooding. Typical infrastructure includes detention basins, diversion berms and cutoff ditches. A landfill liner made of a low conductivity natural or synthetic material (compacted clay or geotextile) is laid out at the bottom of the landfill to prevent or delay the migration of leachate (loaded with micro-organisms, organic and inorganic contaminants) into underlying aquifers and nearby surface water bodies. A typical leachate collection system is made up of hydraulically connected drainage material, leachate collection pipes, riser pipes and submersible pump that collectively function to remove leachate impeded by the liner at the base of the landfill. Failure to control leachate build-up and its removal will most likely cause seepage from the sides and slope instability. A gas collection and recovery system makes it possible for gas generated from waste through biochemical reactions to be pumped out of the landfill to prevent spontaneous fires, gas migration onto adjacent properties, and for use as an energy resource if desirable. A typical set-up includes one or more vertical/horizontal wells strategically positioned within the landfill, a header system to connect gas collection wells to a gas pumphouse system. To purify landfill gas (LFG) for end users, carbon dioxide (CO_2) can be removed by dissolving in water or potassium hydroxide (KOH). In the event LFG is not needed, it can be oxidised using a flare system (Hirshfeld et al .1992, Humer and Lechner, 1999). Noting that water is usually the limiting constraint to microbial activity in a landfill, the primary purpose of a leachate recirculation system is to increase the moisture content of waste contained in the landfill and thereby promote its degradation by micro-organisms. Leachate and/or water can be added by several methods including spray irrigation, surface ponding, sub-surface infiltration, [80] at rates consistent with the moisture absorption capacity of landfill waste, expected leachate outflow rates and capacity of the leachate collection system. An air injection system consisting of vertical screened wells or a horizontal system of pipes connected to blowers injects compressed air into the waste matrix to enhance aerobic decomposition of landfill waste, and reduce the toxicity of methane and waste produced in landfill (Powell et al, 2006). . Similar to sanitary landfills, bulldozers are used to spread and compact solid waste after

---

[80] through wells or infiltration trenches

	it has been deposited by trucks. Daily waste deposits are also covered with soil to reduce odours and provide a firm base upon which vehicles may operate.
Cost	According to Clayton and Huie (1900), annual solid waste disposal costs are estimated at 1.9USD/ton for sanitary landfill facilities handling 100 tons of waste or less in a day. At lager facilities receiving 1,200 tons of waste or higher volumes in a day, the average cost is approximately USD0.65/ton. For bioreactor landfills, additional costs arise from associated fuel/energy consumption needed to inject air and/or leachate into the landfill (Lou and Nair, 2009). Upfront cost may however be partially upset if LFG recovered is used as a source of energy. Similar to sanitary landfill, costs may be compounded by external physical and social costs (Hirshfeld et al., 1992).
Supporting infrastructure	Vehicle wheel cleaning facilities Strategically located scientific monitoring equipment
Advantages	A bioreactor landfill has several advantages. Chief amongst these is the acceleration of degradation processes which speed up the production of landfill gas (LFG), enhance the feasibility of LFG recovery for useful purposes, increase disposal capacity vis-à-vis sanitary landfills, and significantly shortens landfill stabilisation timescales (Powell et al., 2006; Murphy et al., 1995). Overall, bioreactor landfills offer a more sustainable option for waste management (Pacey et al, Undated).
Disadvantages /Challenges	Whereas, leachate management is one of the key strengths of landfill bioreactors, it could also be its weakness. Owing to the heterogeneity of landfill waste and influence of added liquid on air distribution within the waste matrix, differential settling of landfill waste may be induced by addition of liquids. Thus, a tight operating range of moisture content is needed to avoid: 1) compromising the efficiency of the gas collection system; and 2) disruptive back pressure, backflow and leachate surging at injection well heads (Oxarango et al., 2011) N_2O emissions from aerobic bioreactor landfills may be a possible concern in relatively new refuse. the oxidation of methane and non-methane hydrocarbons may also increase CO concentrations from other in-situ processes (Powell et al., 2006). The successful operation of a bioreactor landfill depends upon the degree of control an operator has over dynamic processes occurring within the landfill, underpinned by monitoring and adjusting relevant biological, chemical, and hydrological variables (Pacey et al, Undated).
Abatement potential	LFG capture and flaring (i.e., conversion of CH_4 to CO_2) reduces the global warming potential (GWP) of landfill emissions by 95%. Under controlled conditions, LFG generation is significantly enhanced (Pacey et al, Undated, Reinhart and Townsend, 1997). All things being equal, the mitigation potential of a bioreactor landfill could be twice as large as that of sanitary landfill because of the former’s rapid stabilisation coupled with the additional disposal capacity stabilisation entrains.
Level of penetration	Bioreactor landfills are a completely new technology



Source:
https://www.google.gm/imgres?imgurl=https%3A%2F%2Fwww.researchgate.net%2Fprofile%2FIzzet_Ozturk%2Fpublication%2F223312702%2Ffigure%2Ffig1%2FAS%3A305087541989376%401449749946177%2FFig-1-Schematic-view-of-aerated-landfill-bioreactor.png&imgrefurl=https%3A%2F%2Fwww.researchgate.net%2Ffigure%2F223312702_fig1_Fig-1-Schematic-view-of-aerated-landfill-bioreactor&docid=orgizdFeTlcefM&tbnid=7DCkEDm1POdMcM%3A&w=647&h=372&bih=662&biw=1366&ved=0ahUKEwjr2_HW7PjPAhXTSxoKHRJPDOIQMwhkKEEwQQ&iact=mrc&uact=8

Further Reading

Clayton, K.C. and Huie, J.M., 1900. Sanitary Landfill Cost. *Historical Documents of the Purdue Cooperative Extension Service.* Paper 632. http://docs.lib.purdue.edu/agext/632

Hirshfeld, S, Vesilind, P.A,, Pas. E.I., 1992. Assessing the true cost of landfills. Waste Management and Research, 10, 471-484.

Humer, M., Lechner, P., 1999. Methane oxidation in compost cover layers on landfills. Proceedings of the Seventh International Waste Management and Landfill Symposium 3, 403–410.

Lou, X.F., Nair, J., 2009. The impact of landfilling and composting on greenhouse gas emissions – A review. Bioresource Technology 100, 3792–3798

Murphy, R.J., Jones, D.E., Stessel, R.I., 1995. Relationship of microbial mass and activity in biodegradation of solid waste. *Waste Management. Res. 13*, 485-497.

Oxarango L., Tinet, A.J., Gourc, J.P., Clément, R., 2011. Leachate flows in landfill: laboratory and field scale experiments. Fourth International Workshop “Hydro-Physico-Mechanics of Landfills” Santander, Spain; 27 - 28 April 2011
Powell, J., Jain, P., Kim, H., Townsend, T., and Reinhart, D., 2006. Changes in Landfill Gas Quality as a Result of Controlled Air Injection. Environ. Sci. Technol., 40, 1029-1034

Pacey, J., Morck, R., Reinhart, D. and Yazdani, R. Undated. The bioreactor – an innovation in solid waste management. White Paper. EMCON, San Mateo, California. 14p

Reinhart, D.R., Townsend, T.G., 1997. Landfill bioreactor design and operation, Lewis Publishers, New York, NY, 1997.

Websites
http://ohioline.osu.edu/cd-fact/0139.html
https://en.wikipedia.org/wiki/Bioreactor_landfill

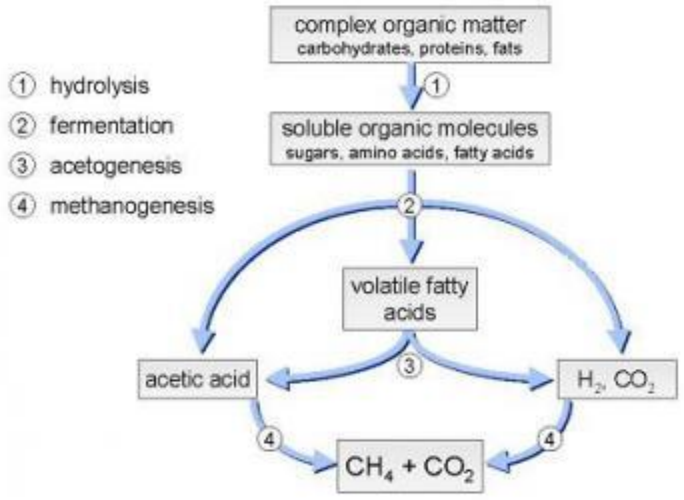
Anaerobic Digester

Defining characteristics	Narrative
General	Anaerobic digestion refers to multiple processes by which micro-organisms break down organic in the absence of oxygen. Quite prominent in some natural settings, these processes can also be replicated in controlled environments to manage waste. The technology to do this is an anaerobic digester/digestion unit which uses the design principle of physical containment to exclude gaseous oxygen from in-vessel reactions (Igoni et al, 2008; Monnet, 2003). Anaerobic digesters are particularly appropriate for wet wastes, and thus used to treat sewage sludge and various organic wastes such as slaughterhouse waste, household waste, etc. Indeed, almost all organic feedstock can be processed with anaerobic digestion; but the putrescibility of waste is an important decision factor if biogas production is one of the key reasons for deployment of the technology (Holm-Nielsen et al. 2009).
Siting and land use	Subject to social and environmental impact assessment guidelines and regulations in force, anaerobic digesters/digestion units, may be suitably located in mixed-residential and industrial areas. Land requirements for installation of these units depend on the size of individual units or cluster of units operated under local or central government authorisation.
Design (components) and Operation	Anaerobic digesters can be designed and engineered to operate using a number of different configurations. Batch-type digesters are the simplest to build. Their operation consists of loading the digester with organic materials and allowing it to digest. Continuous digesters, as the name implies, accommodates a continuous in-stream of feedstock, making the specific technology better suited to wastes capable of flowing on their own, or forming slurries with water (Igoni et al, 2008). To kickstart a digester, common practice is to introduce anaerobic micro-organisms from materials with viable populations in a process known as "seeding" the digesters. This is typically accomplished with the addition of sewage sludge or cattle slurry. Under typical conditions, characteristic micro-organism communities break down complex molecules through hydrolysis,[81] acetogenesis, and acidogenesis to intermediate products, and finally into methane (CH_4), carbon dioxide (CO_2) and digestate (Monnet, 2003). A multi-stage digestion unit permits a greater degree of control of hydrolysis and methanogenesis phases. After sorting or screening to remove physical contaminants from digester feedstock, the latter is often shredded, minced, and pulped in order to speed up digestion processes. Waste characteristics can be altered as well by simple dilution or bulking with compost. Total solid content not only determines the type of pumping technology and energy needed to operate a digestion unit, but also its biogas production. A high degree of control over rate-limiting variables such as temperature, pH, carbon-nitrogen (C/N) ratio, loading rate and moisture content amongst others, is required to achieve optimal performance of an anaerobic digester (Igoni et al. 2008). In a typical digestion system, feedstock residence time takes around 14 days in a one-stage unit, and between 10 and 40 days in a two-stage unit (Uni Idaho, 2014; Holm-Nielsen et al., 2009). Batch reactors are loaded with feedstock that is allowed to ferment and degasify before being unloaded of digestate and a fresh batch of feedstock uploaded (Verma, 2002). Feedstock with a low solid concentration, typically in the form of slurries, is stirred with mixers to create a homogenous mixture, and heated by heat exchangers to accelerate complex breakdown processes, in tanks fitted with outlets for biogas and effluents. High-solids anaerobic digestion units catering for low moisture and high solid wastes not only require lower heating costs, but also less process water delivered through hot water piping. Feedstock is added each day at one end of digester and is decomposed as

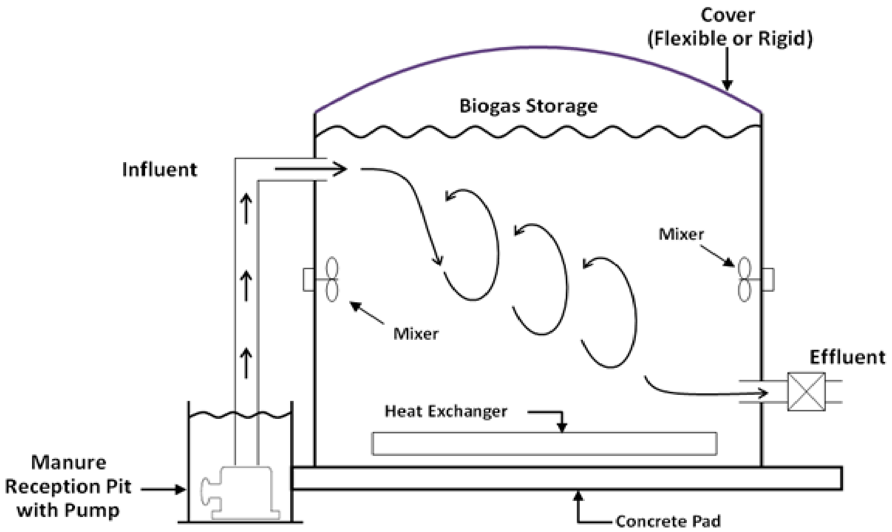
---

[81] Hydrolysis or liquefaction of insoluble materials is the rate-limiting step in anaerobic digestion of waste slurries

	it moves through the unit. Leachate is collected in chambers under the reactors and recycled to the top of each reactor. Waste is kept in reactors until biogas production stops. Gas is piped auxiliary units or storage tanks. Biogas production depends on putrescibility of feedstock, operational parameters of digester and retention time. Impurities found in biogas (i.e. CO_2, H_2S) can be removed by a wide array of physical and chemical measures. Feedstock residues known as digestate is transferred to the storage tanks, which are usually covered with a gas proof membrane for the recovery of the remaining biogas production (Holm, Nielsen et al., 2009). Water from dewatering of digestate is recycled into the reactor and the excess is treated in a wastewater treatment plant. (Levis and Barlaz, 2011)
Costs	Digester sizing and process design directly affect capital cost (Igoni et al (2008), with a batch-digester design being generally less costly. Monnet (2003) indicates that capacity-cost relations are non-linear. According to the author, a plant with processing of 3,000 tonnes/day processing predominantly agrciultural wastes has a capital cost between 100,000 GBP and 200,000 GBP, whereas putting up a 100,000 ton/year plant costs around 500,000 GBP, suggesting cost advantages of larger plants. Source-disaggreagted MSW digestion plants could be several-fold more expensive with a 5,000 tons/year plant costing .2.5 million GBP, and a 100,000 ton/year plant costing up to 12.7 million GBP. Operating costs range from 125,000 GBP 1 million GBP per annum.
Supporting infrastructure	Biogas holder with lightning protection rods and backup gas flare Effluent treatment Waste separation at source
Advantages	Anaerobic digesters have multiple advantages. Crucially, the technology can be deployed on a variety of scales (household, community, municipal). By offering the possibility of diverting biodegradables from dumpsites/landfills, the technology has the potential to reduce landfill requirements, transportation costs, emissions and odours from primitive dumpsites. Furthermore, digestion processes produce recyclable nutrient-rich digestate and effluents that could be used as organic fertiliser. Commercial sales of biogas and digestate could thus offset long-term operating costs. Compared to landfills, digesters produce significantly higher yields of biogas on due to continuous re-circulation of the leachate and higher operating temperatures within a closed system (Verma, 2002)
Disadvantages /Challenges	At least two challenges are associated with the operation of anaerobic digesters. First, health and safety concerns have been raised over explosion risk (Monnet, 2003; Verma, 2002), and second, the reliability of feedstock supply chains, itself linked to uncertainties/weaknesses related to availability and collection of waste streams. Both concerns/challenges could be tackled with adequate fire safety measures in place one hand, and integration of performance metrics with facility size and location factors at the feasibility study stage, on the other.
Abatement potential	An anaerobic digester operated under conditions of biogas recovery and use as a source of energy has high abatement potential compared to other waste management technologies, especially when waste is segregated at source and contains or contains a large fraction of biodegradables. Levis and Barlaz (2011), in a life-cycle assessment, report 395 kg$CO2_e$ in avoided emissions from conventional electricity power plants and soils, as a result of operating a digestion unit processing 1.5 tonnes of food and other biodegradable waste. In comparison, composting led to GHG abatement ranging from 64 to 148kg$CO2_e$, whilst the best result for landfill alternatives was 240 kg $CO2_e$ reduction.
Level of penetration	20 small units built under Peri-urban Smallholder Project with mixed results (AF-MERCADOS, 2013)



Source:
https://www.google.gm/imgres?imgurl=http%3A%2F%2Fwww.climatetechwiki.org%2Fsites%2Fclimatetechwiki.org%2Ffiles%2Fimages%2Fextra%2Ffeat11_picii-1_0.jpg&imgrefurl=http%3A%2F%2Fwww.climatetechwiki.org%2Ftechnology%2Fjiqweb-anbt&docid=2HGvPdRcEHmyaM&tbnid=uYJEGc3hwkfzPM%3A&w=480&h=360&bih=662&biw=1366&ved=0ahUKEwiVrp3ZyvjPAhWCORoKHWbcAMUQMwiKAShSMFI&iact=mrc&uact=8



Source:
https://www.google.gm/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwjJhIygy_jPAhVJrxoKHezRAukQjRwIBw&url=http%3A%2F%2Fwww.plugflowdigester.com%2F&bvm=bv.136593572,d.d2s&psig=AFQjCNFkRePOLZljDwUgBd-bbX9_iaYZjg&ust=1477575332270881

Further Reading

AF-MERCADOS EMI, 2013, Electricity Strategy and Action Plan. Consultancy report prepared for the Ministry of Energy, Banjul, 66p+Annexes.
Holm-Nielsen, J.B., Al Seadi, T. and Oleskowicz-Popiel, P., 2009. The future of anaerobic digestion and biogas utilization. Bioresource Technology 100, 5478–5484
Igoni, A.H., Ayotamuno, M.J., Eze, C.L., Ogaji, S..T., and Probert, S.D., 2008. Designs of anaerobic digesters for producing biogas from municipal solid-waste. Applied Energy 85, 430–438.

Levis, J.W. and Barlaz, M.A., 2011. What Is the Most Environmentally Beneficial Way to Treat Commercial Food Waste? Environ. Sci. Technol., 45, 7438–7444

Monnet, F., 2003. An introduction to anaerobic digestion of organic wastes. Report by Remade Scotland. 48p. http://www.remade.org.uk/media/9102/an%20introduction%20to%20anaerobic%20digestion%20nov%202003.pdf

University of Idaho, 2014. Anaerobic digestion basics. CL1215.

Verma, S. 2002. Anaerobic digestion of biodegradable organics in municipal solid wastes. Unpublished MSc thesis. Columbia University. Department of Earth and Environmental Engineering. 50p.

Websites

https://en.wikipedia.org/wiki/Anaerobic_digestion
https://en.wikipedia.org/wiki/Waste_management
http://water.me.vccs.edu/courses/ENV149/lesson4b.htm

Waste Incinerator (Moving Grate)

Defining characteristics	Narrative
General	In small volumes generally composed of combustible materials, waste has been traditionally piled up, set alight and left to burn itself out. In recent decades, burn barrels have also emerged on the technological landscape of waste management, as a low-cost and safer form of waste incineration. However, neither burn piles nor burn barrels provide a long-term solution to the problems posed by increasing solid waste streams made up of mixed waste of diverse physical and chemical characteristics. The thrust of modern thermal treatment technologies therefore is to reduce health risks, recover valuable resources,[82] and reduce the volume of incineration residues, the latter mostly made up of inorganic waste constituents. Consistent with forces driving innovation, incinerators configured as waste-to- energy (WtE) plants are available in many designs from Asian, European and US constructors. Worldwide, the type of incinerator most widely used for processing municipal solid waste is the moving grate incinerator, to the effect that the incinerator is sometimes referred to as the municipal solid waste incinerator (MSWI).
Siting and land use	Ideally, the site chosen for installation of an incinerator plant should not should not cause environmental impacts including disruption of ecosystems on contiguous land in breach of established in legal statues or industry standards. Social costs and acceptability should also be considered and discussed with communities living in close proximity to potential incinerator sites. Alternative land uses forecast over the life span of the plant could be equally important. As a general rule, MSWIs should be located on land dedicated to medium-size and heavy industries.
Design (components) and Operation	An MSWI has the following key components: 1) waste bunker; 2) feeders, furnace; 4) flue gas cleansing system; and 5) ash pit. One or more waste bunkers constitute holding areas with capacity to store weekly volumes of waste delivered to incineration plant. In order o minimise floor area occupied by bunkers, these are often sunk below ground level. These are contraptions used to channelise waste into the incinerator's combustion chamber. In some designs, a screw feeder device is used, but more often than not, incinerators rely on a feeding mechanism comprising an overhead rail system (inside bunkers) equipped with grabs, hopper and a strategically positioned ram to poke waste into the combustion chamber of the furnace. The furnace, designed to withstand temperatures up to 1,400°C, incorporates a moving grate, air inlets, and bottom ash collector, flue gases outlet, and, in WtE plants, has an in-built boiler. A porous moving grate[83] sloping towards an ash collector represents a sort of conveyor on which solid waste is exposed to ignition temperatures and incinerated. Air inlets positioned above and below the moving grate provide the means of injecting calibrated levels of preheated air into the chamber to ensure complete oxidation of waste. The timing of waste introduction and control of burn conditions are important considerations for complete combustion and avoidance of plant shutdowns. High temperatures in particular are required for complete combustion of wastes (Byeong-Kyu et al., 2004; Nussbaumer, 200). If present, a boiler uses heat from burning waste to generate steam that is piped into a steam turbine to generate electricity. Flue gases from the combustion chamber are transported through a complex treatment system designed to remove particulate matter and hazardous chemicals. To this end, flue gas passes through wet scrubbers and sets of filters, arranged in series to ensure that plant emissions meet regulatory standards. Electrostatic precipitators and fabric filters installed downstream of the combustion chamber minimise the release of dioxins, furans, heavy metals, and other harmful chemicals (Mukerjee et al., 2016). Treated flue gases are released into the

---

[82] In thermal treatment technologies designed to break down organic wastes in absence of oxygen (i..e pyrolysis process), gases produced from heating organic wastes condense to biodiesel (synthetic fuel).

[83] The moving grate is made of corrosion-resistant alloys with large tolerance for high temperatures.

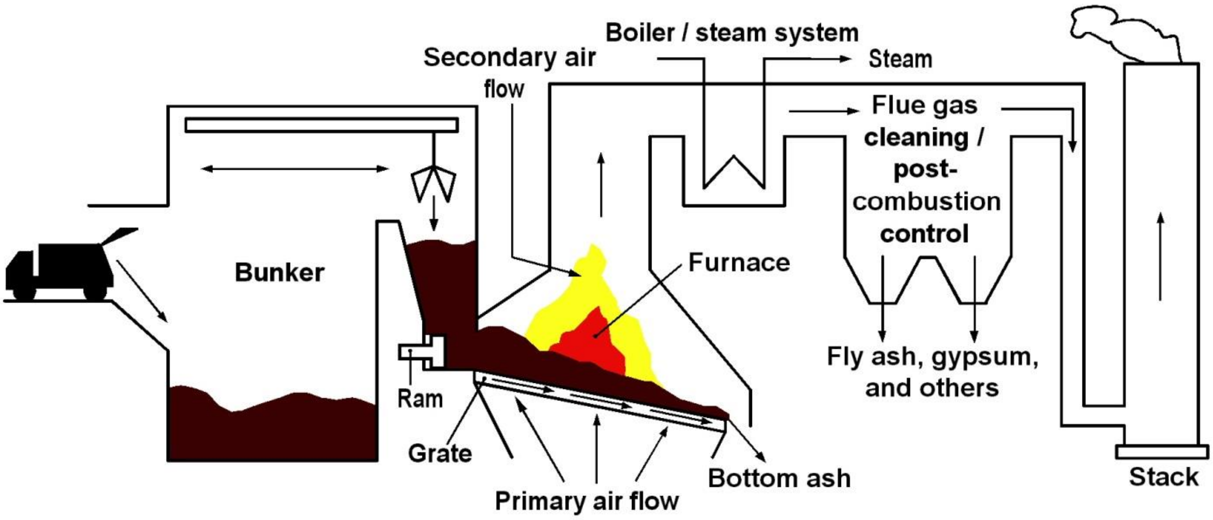
	atmosphere via a chimney stack of appropriate height. An ash pit collects end product of combustion coming off at the end of the moving grate. These are passed over with an electromagnet to extract useful metals. Ash is then removed through a water lock, and residues disposed of in landfills or reused as construction and road-building material after undergoing some form of treatment (Sakai and Hiraoka, 2000). Water used in all process is recycled.
Costs	According to (Ayalon et al., 2001), the investment cost of an incinerator with a processing capacity of 500ton/day is USD50 million; five-fold higher than the investment in an anaerobic plant of equal capacity. Depending on the nature and moisture content of waste, Byeong-Kyu et al (2004) report treatment costs in the range of 0.12 USD/kg (general waste) to 3.44USD/kg. In the same vein, Park and Jeong (2000) point out that treatment or disposal costs of infectious waste by incineration could be 10 to 20 times higher than corresponding costs for non-infectious wastes. Using specific assumptions about energy recovery from waste incineration, Rabl et al (2008) found the damage cost of incineration to be between 4 and EUR21/metric ton of waste, compared with EUR10 to EUR13 per metric ton of waste for landfilling options
Supporting infrastructure	Transport Electricity generation and transmission infrastructure (in case MSWI configure as part of WtE) District heating infrastructure (optional) Treatment and disposal plant/facility (for wastewater from scrubbers)
Advantages	Moving grate incinerators have several comparative advantages vis-à-vis other waste treatment technologies. In no particular order of importance, these incinerators can accommodate large quantities and variations in MSW composition. In addition, the technology is particularly suited for disposal of hazardous waste (biomedical), special waste (car tyres), and residues of other solid waste and wastewater management processes. Compared to other thermal treatment technologies, it has the highest processing capacity[84] and high reliability[85] , and does not require as much area as landfills (Rabl et al. 2008). Moving grate incinerators substantially reduce the weight (up to 75%) and volume (up to 90%) of solid waste, and are highly efficient in capturing generated energy.
Disadvantages /Challenges	Incinerators command high investment and operating costs. Although end of pipe treatment of flue gases should ensure plant emissions are below regulated standards, public perception of health risks is still a major factor in resistance to the technology (Rabl et a. 2008). The tendency not to segregate waste destined for incineration could also curtail alternative treatment and/or uses of organic wastes.
Abatement potential	Incineration of 1 ton of MSW produces approximately 1 ton of carbon dioxide (CO_2). If on the other hand, the same waste is was sent to a landfill, it would produce approximately 62 cubic metres of methane (CH_4) through anaerobic decomposition.[86] Within a time horizon of 20 and 100 years, the weight of 62 cubic meters of $CH_4$from landfill operations or fugitive emissions is approximately 2.93 and 0.98 tonnes of CO_2, respectively.
Level of penetration	The moving grate incinerator is a completely new technology

---

[84] Up to 4,000 tonnes of waste per day

[85] Capable of continuously for 8,000 hours per year[85] with only a month-long scheduled stop for inspection and maintenance

[86] Methane production actually depends on waste composition



Source: http://www.dcsc.tudelft.nl/Research/Old/project_ml_pvdh_ob.html

Further Reading

Ayalon, O., Avnimelech, Y., Shechter, M., 2001. Solid waste treatment as a high-priority and low-cost alternative for greenhouse gas mitigation. Environmental Management Vol. 27, No. 5, pp. 697–704. DOI: 10.1007/s002670010180

Byeong-Kyu L., Ellenbeckerb, M.J., and Moure-Ersasob, R., 2004. Alternatives for treatment and disposal cost reduction of regulated medical wastes. Waste Management 24 (2004) 143–151.

Mukherjee, A., Debnath, B., Ghosh, S.K., 2016. A Review on Technologies of Removal of Dioxins and Furans from Incinerator Flue Gas. Procedia Environmental Sciences, 35, 528 – 540.

Nussbaumer, T., 2003. Combustion and co-combustion of biomass: Fundamentals, technologies, and primary measures for emission reduction. *Energy & Fuels 17*, 1510-1521

Park, H.S., Jeong, J.W., 2001. Recent trends on disposal technologies of medical waste. J. Korean Solid Wastes Engineering Soc. 18 (1), 18–27.

Rabl, A., Spadaro, J.V., Zoughaib, A., 2008. Environmental impacts and costs of solid waste: a comparison of landfill and incineration Waste Management & Research, 26, 147–1, 62

Sakai,S., Hiraoka, M., 2000. Municipal solid waste incinerator residue recycling by thermal processes Waste Management, 20, 249 - 258

Websites

https://en.wikipedia.org/wiki/Furnace
https://en.wikipedia.org/wiki/Incineration
http://www.bioenergyconsult.com/moving-grate-incineration/
http://www.sswm.info/content/incineration-large-scale
https://www.google.gm/search?q=municipal+solid+waste+incinerators&biw=1366&bih=613&tbm=isch&tbo=u&source=univ&sa=X&ved=0ahUKEwj_pNvltd_PAhWGQBoKHUxJBGoQsAQIPw&dpr=1

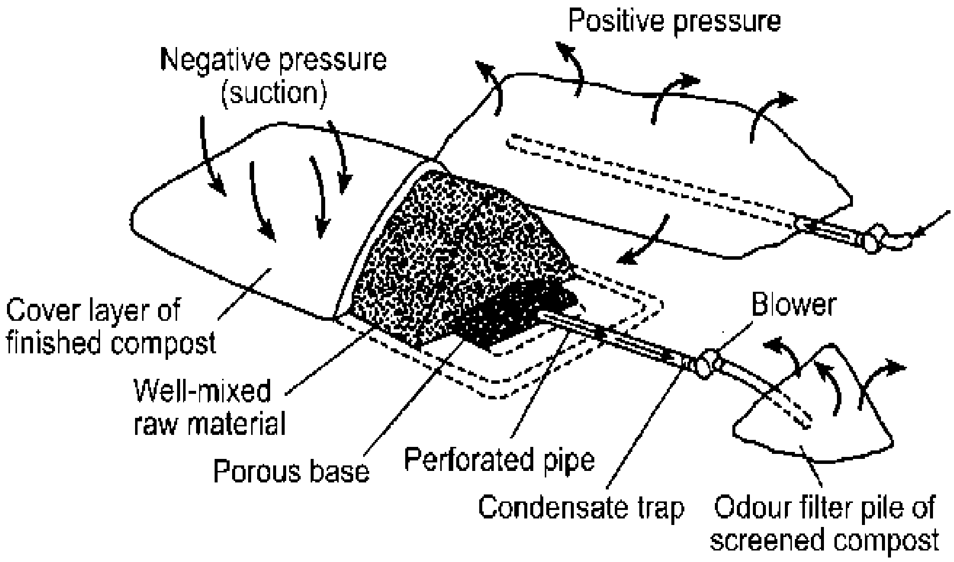
Aerated Static Pile (composting)

Defining characteristics	Narrative
General	Composting is a waste management practice in which organic waste, placed in natural or engineered environments, is transformed by micro-organisms after a period ranging from weeks to months into friable biosolids an, carbon dioxide (CO_2) and possibly leachates. Various researchers including Levis and Barlaz (2011) and Renkow and Rubin (1998) recognise composting alternatives of varying technological sophistication, based on anaerobic and aerobic principles (Jakobsen, 1994). For large-scale composting operations,[87] the most prominent amongst the latter group include windrows and aerated static pile (ASP (systems). ASP is different from windrow composting with respect to physical manipulation of the blended mixture of organic waste materials during composting. ASP composting systems work well with wet materials and large volumes of treatable organic waste. The safety of compost is assessed by several methods emphasising the stability of organic matter content and absence of pathogens (Bernal et al., 1998; Jackson and White; 1997; Zucconi et al., 1981).
Siting and land use	Key factors in siting of composting facilities include the volume of raw materials anticipated and kind of machinery and equipment to be used for various activities in the composting process (Wei et al,. 2001). Other factors to consider include road accessibility, susceptibility to flooding, and alternative land uses. Proximity of potential sites to major sources of feedstock/raw materials and low ground and surface water contamination risks may constitute significant advantages. Other environmental and social impact criteria may come into play as part of mandatory permitting processes. From an operational standpoint, a facility implanted in a rectangular- or square-shaped area is preferred over one that is located an irregularly shaped area. ASP facilities can be under roof or outdoors.
Design (components) and Operation	Aerated static piles are elongated mounds of well-mixed, uniform compost materials, formed using a front-end loader. Typically, piles are 1 to 2 metres high, 2 to 3.5 metres wide at the base, and tens of metres in length, organised as parallel structures separated by alleyways at least 1.5 metre wide. Compost materials are usually piled on top of a 6-inch base of porous material such as wood chips, chopped straw, under which a network of pipes serve to force air into the pile to ensure adequate aeration within compost mass. In some variants, pipe networks are installed on top of a floor prior to the build-up of compost piles, or buried within the pile during its buildup (Renkow and Rubin, 1998). It is customary to pave surfaces on which wet compost material is placed, and considered good practice to build berms around the perimeter to control diffuse runoff headed towards or moving away from the site. The aeration system which gives the system its name uses a centrifugal blower or axial flow fan to push and/or pull air through the composting mass at fixed rate or variable rates. In large-scale systems, forced aeration system is coupled to a computerised monitoring system that controls aeration rates of the composting mass (Leton and Stentiford, 1990). An adequate oxygen supply is essential for achieving good composting results and controlling the formation of odours from decomposing material (Rasapoor et al., 2009; Sesay et al., 1998; Fernandes and Sartaj, 1997). To prevent the compost from drying out, the initial moisture content of compost piles is adjusted by mixing with high moisture materials and optimised to stay within the preferred range of 50 to 60% to support microbial activity during decomposition (Luo et al., 2008). Some piles equally feature an insulating layer of compost or bulking agent reduce moisture loss, retain heat, curtail the proliferation of egg-laying flies, and act as a biofilter for odours.
Costs	The literature on ASP systems contains sparse information on development and

---

[87] Industrial/Municipal

	operational costs. Most authors deliberately sideline the question of cost because costs are closely tied to the specificities of each site. Renkow and Rubin (1998) found composting costs of around USD50/metric ton from a sample of 19 sites in the US, simultaneously pointing out that very few facilities receive any revenues from the sale of compost to offset operating costs. According to Wei et al (2001), the costs of building and operating ASP vary considerably between locations from USD1.5 million to USD15 million. In most of the cases reported, capital costs significantly outweigh operating costs. Costs taking account of processing capacity range from USD55 to USD187 per metric ton of dry matter depending on the type of system and waste characteristics.
Supporting infrastructure	Apart from a fence to control access to the site, auxiliary infrastructure as follows might be required on site: Retainer walls for storage piles Office and lab Storage and tool building, Maintenance shed Other machinery used in composting facilities includes conveyance devices, loaders, screening equipment, and baggers.
Advantages	ASP systems combine the advantages of composting methods notably recovery and transformation of organic wastes into valuable resources, avoiding in the process unnecessary landfilling of biodegradable wastes and emission of greenhouse gases (GHGs) and volatile organic compounds (VOCs). In addition, the ASP method is very versatile. It can be operated with mobile and light power supply solutions (including solar) at multiple scales of operation. Compared with windrows, ASP optimises the use of land area and significantly improves the cost-effectiveness of composting operations (Oonk and boom, 1995). Parasites, pathogens and weed seeds are eliminated within 3 days, mature compost ready within 3 to 5 week.
Disadvantages /Challenges	ASP composting requires strict waste segregation. This could be a handicap in places where logistics problems hinder the separation of waste streams at source. Compared to in-vessel composting and anaerobic digestion, ASP operations also require a much larger land area.
Abatement potential	Lou and Nair (2009) point out that GHG emissions from the composting process is highly dependent on characteristics of feedstock that vary widely from “green” to “brown” wastes with various mixtures in-between. In general, feedstock with a higher dissolved organic carbon (DOC) will produce higher GHG emissions. In this regard, Andersen et al. (2009) report finding emissions ranging from 0.081 to 0.141 ton CO_2-eq from compositing operations using garden wastes. By comparison, Lou and Nair (2009) cite studies in which theoretical estimates of GHG emissions range from 0.284 to 0.323 ton CO_2-eq per ton of mixed waste were reported. Little is known regarding N_2O emissions produced by either incomplete ammonium oxidation or via incomplete denitrification of compost mass (IPCC, 2006).
Level of penetration	ASPs are a completely new technology



Source:
https://www.google.gm/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&cad=rja&uact=8&ved=0ahUKEwjVibOkyfjPAhVBPxoKHd5lBZ8QjRwIBw&url=http%3A%2F%2Fwww.fao.org%2Fdocrep%2F007%2Fy5104e%2Fy5104e07.htm&psig=AFQjCNHrpAc02W0UwO2l7KtlMISfKyYjAQ&ust=1477574614416515

Further Reading

Andersen, J.K., Boldrin, A., Samuelsson, J., Christensen, T.H., Scheutz, C, 2009 . Quantification of Greenhouse Gas Emissions from Windrow Composting of Garden Waste Journal of Environmental Quality, Vol. 39 No. 2,*713-724*
Bernal, M.P., Paredes, C., Sanchez-Monedero, M.A., Cegarra, J. 1998. Maturity and stability parameters of composts prepared with a wide range of organic wastes.. Bioresource Technology 63, 91-99

Fernandes, L., Sartaj, M., 1997. Comparativen study of static pile composting using atural, forced and passive aeration methods. Compost Science & Utilization, 5:4, 65-77, DOI: 10.1080/1065657X.1997.10701899

IPCC (Intergovernmental Panel on Climate Change), 2006. IPCC Guidelines for National Greenhouse Gas Inventories.

Jackson, M.J., Line, M.A., 1997. Windrow composting of pulp and paper mill sludge:
Process performance and assessment of product quality. Compost Science & Utilization, Vol. 5, No.3, 6-14

Jakobsen, S.T., 1994. Aerobic decomposition of organic wastes: I. Stoichiometric calculation of air change. Resources, Conservation and Recycling 12,165-175

Leton, TG., Stentiford, EI. 1990. Control of aeration in static pile composting. Waste Management and & Research, 8, 299 – 306

Levis, J.W., Barlaz, M.A., 2011. What Is the Most Environmentally Beneficial Way to Treat Commercial Food Waste? Environ. Sci. Technol., 45, 7438–7444

Lou, X.F., Nair, J., 2009. The impact of landfilling and composting on greenhouse gas emissions – A review Bioresource Technology, 100, 3792–3798

Luo, W., Chen, T.B., Zheng, G.D., Gao, D., Zhang, Y.A., Gao, W., 2008. Effect of moisture adjustments on vertical temperature distribution during forced-aeration static-pile composting of sewage sludge. Resources, Conservation and Recycling 52 (2008) 635–642

Oonk, J., and Boom, A., 1995. Landfill gas formation, recovery and emissions. In: Pipatti, R., Wihersaari, M., 1998. Cost-effectiveness of alternative strategies in mitigating the greenhouse impact of waste management in three communities of different size. Mitigation and Adaptation Strategies for Global Change 2, 337–358.

Rasapoor, M., Nasrabadi, T., Kamali, M., Hoveidi, H., 2998. The effects of aeration rate on generated compost quality, using aerated static pile method. Waste Management 29 (2009) 570–573

Renkow, M., Rubin, A.R., 1998. Does municipal solid waste composting make economic sense? Journal of Environmental Management, 63, 339 - 347.

Sesay, A., Lasaridi, KE, Stentiford, EI, 1998. Aerated static pile composting of municipal solid waste (MSW): a comparsion of positive pressure aeration with hybrid positive and negative aeration. Waste Manage Re, 1998, 16, 264 - 272

Wei, Y.S., Fan, Y.B., Wang. M.J., 2001. A cost analysis of sewage sludge composting for small and mid-scale municipal wastewater treatment plants. Resources, Conservation and Recycling 33, 203–216

Zucconi, F., Pera, A., Forte, M. and de Bertoldi, M. (1981). Evaluating toxicity of immature compost BioCycle, 22, 54-57.

Websites

https://en.wikipedia.org/wiki/Compost
https://en.wikipedia.org/wiki/Aerated_static_pile_composting
http://www.yuckyducky.com/composting/aerated-static-pile-composting/
https://www.google.gm/search?q=aerated+static+pile+composting&biw=1366&bih=662&source=lnms&tbm=isch&sa=X&ved=0ahUKEwj36tTNx_jPAhWHMhoKHVCpAA4Q_AUIBigB&dpr=1

Technology factsheets_transport

Direct (fuel) Injection System

Defining characteristics	*Narrative*
General	Modern light- and heavy-duty road vehicles are predominantly powered by internal combustion engines (ICEs) running on energy-dense fuels such as petrol[88] or diesel. Essentially, ICEs rely on the synchronous operation of air-supply and fuel-supply sub-systems. In a vehicle running on petrol, a carburetor, historically, represents the intersection of these two sub-systems, vaporises the fuel stream thus allowing it to mix with an incoming airstream before induction into the engine cylinders where combustion generates a motive force that drives the vehicle's powertrain. With environmental concerns gaining traction on the global policy agenda, and environmental standards driving technological innovations on several fronts, fuel injector systems were first introduced as substitutes for carburetors by the automobile industry in the 1980s. One type of fuel injection system; port fuel injection or indirect fuel injection system, works by spraying a mist of fuel through a small nozzle at a pressure of 2.5 to 4.5 bars over the intake valve head where the fuel mist mixes with air in specific proportions, ideally 14.7 parts of air to 1 part of fuel by mass, in readiness for combustion inside engine cylinders. A second type of injection system, conceptually associated with diesel engines, sprays with precise timing an ultra-fine mist of fuel directly into individual engine cylinders. The main benefits to an electrically operated and electronically controlled direct injection system is that at all times a vehicle is on the road, a finely calibrated amount of fuel can be injected into its engine cylinders in response to the engine's operating conditions, resulting in higher power output, improved fuel efficiency and lower GHG emissions.
Siting and land use	Screwed into vehicles' engine cylinder heads
Design (components) and Operation	An electrically operated and electronically controlled direct injection system comprises three basic components: 1) high pressure fuel pump; 2) fuel pressure sensor; and 3) injectors; operationally controlled by a vehicle's engine control unit (ECU); an onboard micro-computer that directs various sub-systems of the vehicle by actuating certain key components and monitoring engine performance through feedback from multiple sensors. A high pressure fuel pump lifts fuel from a vehicle's fuel tank to injectors mounted on an onboard engine. Externally, a high pressure fuel pump has a fuel inlet and high pressure fuel outlet. Most pumps in this category are single piston pumps mechanically-driven by the host vehicle's camshaft. As a pump's plunger retreats, the primary electric pump fills up the chamber with fuel at about 3 to 5 bars. On the forward movement of the plunger, fuel is pressurised well beyond 100 bars. An internal pressure control solenoid sets a limit to the maximum operating pressure and returns excess fuel to the pump intake, when engine demand is relatively low. A high pressure fuel outlet transports fuel at a controlled flow rate and pressure to the fuel rail. A high pressure fuel sensor fitted to the fuel rail monitors fuel pressure and continually sends a modulated signal to the ECU which actuates the high pressure pump solenoid as required to adjust pressure of fuel pumped to the rail (Fiengo et al., 2013; Çelik and Ozdalyan, 2010). A pressure regulation electro-valve on the fuel rail returns excess fuel to the tank. Under its own pressure, fuel flows into the chamber and nozzle of a solenoid-operated fuel injector, but remains sealed off from associated engine cylinder by a pressure valve. Fuel injection occurs when the when the solenoid winding is activated by a trigger

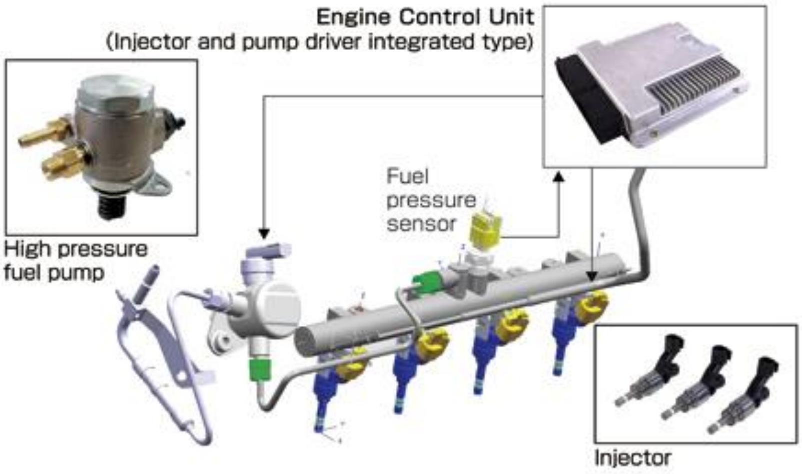
---

[88] gasoline (in the US)

	current from the ECU thus generating a magnetic field that lifts the injector pintle off its seat releasing an atomized jet of fuel droplets with a Sauter mean diameter (SMD)[89] no larger than 20 microns in a 10 to 15 degree spray angle from the injector nozzle. Pulse of fuel injected into the combustion chamber generally lasts between 0.4 and 5 microseconds, and end when the injector's solenoid winding is de-energised and the pintle returns to its rest position. An O-ring on nozzle tip prevents gases leaking out of the cylinder and the nozzle's plastic tip insulates injector from heating. Additional to the customary fuel filter that removes gross-sized impurities from fuel stream, the injector incorporates a filter to trap microscopic-sized fuel contaminants Fiengo et al., 2013; Çelik and Ozdalyan, 2010; Alkidas, 2007, Zhao et al., 1999)
Cost	In new vehicles, the cost of direct injection systems is inseparable from the vehicle cost which itself is strongly correlated to performance-related specifications such as volumetric displacement, top speed, range, acceleration, tailpipe emissions, and brand name as well. Thus, indicative costs of a 1,300 and 1,600cc vehicles fitted with direct injection technology lies between 19,000 and 22,000 Euros, with corresponding powertrain specific costs of 50.9 and 67.3 Euro/kW (Thiel et al, 2010). Assuming, a retrofit strategy is adopted by policy-makers/owners, the cost of direct injection unit approximates the market price of key component parts, cost of engine modifications and professional fees of engineer carrying out retrofit. At this point, a conservative estimate of direct injection retrofit cost falls within the range 1,300 to 1,550 Euros.
Supporting infrastructure	High quality roads
Advantages	GDI fuel mixing strategy gives better volumetric efficiency, fuel economy, engine power compared with port fuel injected and carburetted engines (Fiengo et al., 2013; Zhao et al., 1999) About 35% greater fuel economy than carburetted engines (Kobayashi et al., 2009) Power and torque higher than PFI engines by 20% and 35% (Çelik and Ozdalyan, 2010) Lower exhaust emissions (Çelik and Ozdalyan, 2010)
Disadvantages /Challenges	Can slightly increase unburnt hydrocarbons in emissions at idle and partial engine loads (Çelik and Ozdalyan, 2010; Zhao et al., 1999) Causes relative increase in NO_X emissions compared to carbureted engines
Abatement potential	Greenhouse emissions reduction attributable to GDI engine fuel economy (Fiengo et al., 2013; Sullivan et al., 2004; Zhao et al., 1999) is mediated by a complex function of engine make, fuel type, fuel quality vehicle loads and driving patterns. CO_2 emissions reductions derived from literature range between 40 and 75gCO_2/km (Sullivan et al., 2004; Zhao et al. 1999). In cars operating on a GDI engine and low-sulfur fuel, emissions of oxides of nitrogen (NO_x) are lower by 40% but weighted-average emissions total hydrocarbon emissions linked to in-cylinder wetting are significantly 3 to 10 times higher than those from a PFI vehicle (Li et al., 2000; Cole et al., 1998).
Level of penetration	Less than 40% of national vehicle fleet estimated to be running on diesel compression ignition engines.

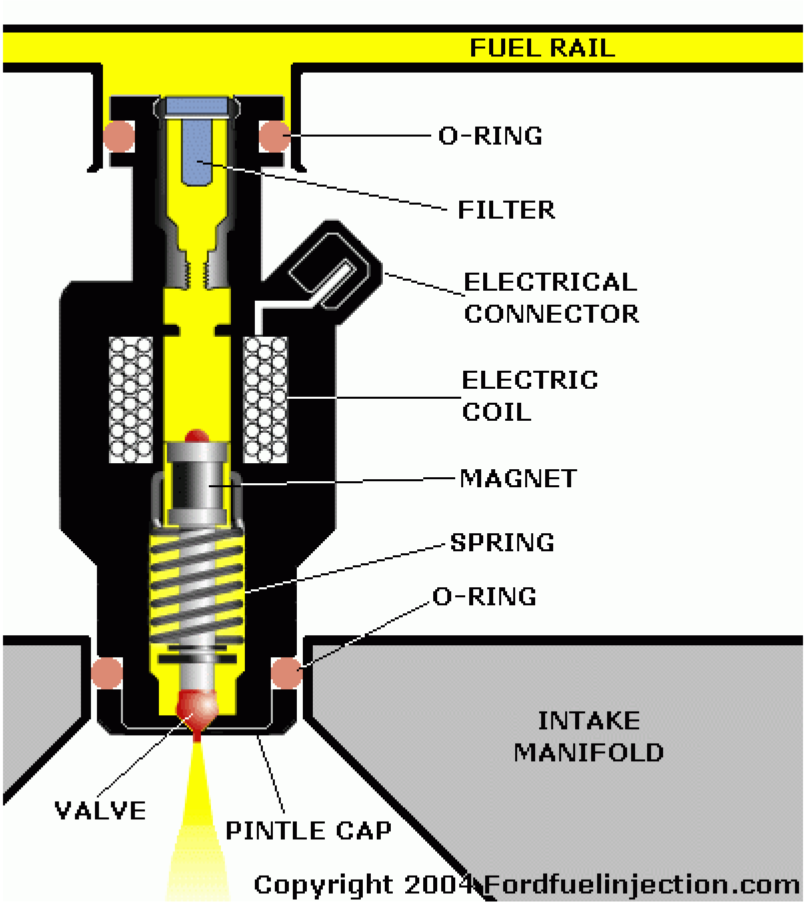
---

[89] The SMD is defined as the diameter of the droplet having the same surface to volume ratio as that of the overall spray (Fiengo et al., 2013)

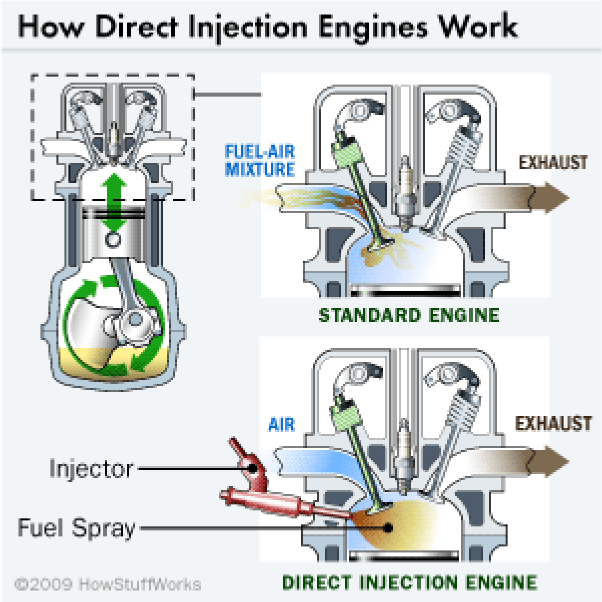


Source: https://www.hitachi-automotive.us/images/Products/OEMproducts/products_ems_01_photo02.jpg

Source: http://www.autodiagnosticsandpublishing.com/feature/fuel-injector-testing_files/Fuel%20Injector.jpg



Source: http://www.protowrxs.com/OldFuelInjection/Images/injector02.gif



Source: http://s.hswstatic.com/gif/direct-injection-engine-2.gif

Further Reading

Alkidas, A.C., 2007. Combustion advancements in gasoline engines. Energy Conversion and Management 48, 2751–2761

Çelik, M.B., Ozdalyan, B., 2010. Gasoline Direct Injection, Fuel Injection, Daniela Siano (Ed.), ISBN: 978-953-307-116-9, InTech.
Available from: http://www.intechopen.com/books/fuelinjection/gasoline-direct-injection

Cole, R., Poola, R., and Sekar, R., "Exhaust Emissions of a Vehicle with a Gasoline Direct-Injection Engine," SAE Technical Paper 982605, 1998, doi:10.4271/982605.

Fiengo, G., Gaeta, A., Palladino, A., Giglio, V., 2013. Basic Concepts on GDI Systems
in Common Rail System for GDI Engines: Modelling, Identification and Control, pp 17 -33. Springer Briefs in Electrical and Computer Engineering. DOI: 10.1007/978-1-4471-4468-7_2.

Kobayashi S., Plotkin, S. Ribeiro, S.K., 2009. Energy efficiency technologies for road vehicles. Energy Efficiency 2:125–137. DOI 10.1007/s12053-008-9037-3

Li, J. Huang, Y., Alger, T.F., Matthews, R.D., Hall, M.J., Stanglmaier, R.H., Roberts, C.E., Dai, W., Anderson, R.W., 2000. Liquid Fuel Impingement on In-Cylinder Surfaces as a Source of Hydrocarbon Emissions From Direct Injection Gasoline Engines**.** *J. Eng. Gas Turbines Power* 123(3), 659-668. doi:10.1115/1.1370398

Sullivan, J.L., Baker, R.E., Boyer, B.A., Hammerle, R.H., Kenny, T.E., Muniz, L., Waalington, T.J., 2004. CO_2 Emission Benefit of Diesel (versus Gasoline) Powered Vehicles. Environmental Science & Technology. Vol, 38, No. 12, 3217-3223

Thiel, C., Perujo, A., Mercier, A. 2010. Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios. Energy Policy 38, 7142–7151.

Zhao, F., Lai, M.C., Harrington, D.L., 1999. Automotive spark-ignited direct-injection gasoline engines. Progress in Energy and Combustion Science 25 (1999) 437–562

Websites
https://en.wikipedia.org/wiki/Internal_combustion_engine
https://www.howacarworks.com/basics/how-a-fuel-injection-system-works
https://en.wikipedia.org/wiki/Engine_control_unit

Turbocharger

Defining characteristics	*Narrative*
General	Modern light- and heavy-duty road vehicles are predominantly powered by internal combustion engines (ICEs) running on energy-dense fuels such as petrol[90] or diesel. In an ICE, combustion of a fuel-air mixture inside engine cylinders generate a motive force that drives the vehicle's powertrain and releases heat energy and exhaust gases through the vehicle's exhaust manifold and finally to the environment. Essentially, engine performance is related to the composition of fuel-air mixture, ideally 14.7 parts of air to 1 part of fuel by mass, obtained from synergistic operation of air-supply and fuel-supply sub-systems. Past methods for optimising fuel-air mixtures include fuel modifiers[91] to increase cylinder compression ratios, whilst current trends in combustion management focus on dynamic control over air supply and/or fuel supply systems. A practical method for increasing air and by extension oxygen supply to engine cylinders is forced air induction with superchargers or turbochargers. The latter piece of technology, which evolved from mechanically driven superchargers, exploit the heat and pressure energy contained in vehicle exhaust gases to improve compression ratio resulting in higher power output, improved fuel economy and lower emissions of GHGs and particulate matter (Saidur et al, 2012; Berggren and Magnusson, 2012). With environmental concerns gaining traction on the global policy agenda, and environmental standards driving technological innovations on several fronts, turbochargers[92] are arguably one of the most important technologies for the automotive industry. For manufacturers, the use of turbochargers enables reduction of engine cylinder volumes and weight without reducing engine power produced (Galindo et al. 2013; Jinnai et al., 2012; Uchida, 2006)
Siting and land use	Bolted to the exhaust manifold of vehicle engines

---

[90] gasoline (in the US)

[91] Products added directly to fuel included lead (now outlawed in many countries), catalysts and other commercial formulae

[92] A well established technology in the diesel industry, especially on heavy duty vehicles

Design (components) and Operation	A turbocharger is a device that serves to pump extra air into a vehicle's combustion chambers during the downward stroke phase of the combustion cycle. It is composed of a shaft with turbine wheel attached at one end (inlet) and compressor wheel at the other (outlet) assembled within a centre housing and rotating assembly (CHRA), and waste gate valve in some designs. The CHRA also contains a bearing system supporting the shaft and protecting the turbine from damage when operating at very high speeds. As exhaust gas from engine cylinders pass through the turbocharger inlet, latent heat and pressure energy spin the the turbocharger turbine, which moves the compressor that shares a common shaft with the turbine. In turn, the compressor draws in ambient air, accelerates it to a high velocity raising its pressure in the process and dispatches this pressurised mass of air through an intercooler to the intake manifold where a correspondingly greater mass of air is fed into engine cylinders on each intake stroke.[93] The sharp increase in intake air pressure, commonly referred to as boosting is limited by the engine displacement, engine speed, throttle valve opening, and the size of the turbocharger.[94] A pressure sensor installed in the intake manifold monitors and transmits air pressure proxy variables to the engine control unit (ECU) which actuates a waste gate (by-pass valve) when air pressure exceeds a pre-programmed threshold, thus regulating exhaust gas flow to turbines.[95] Exhaust gas diverted through the waste gate not only depresses turbine speed (i.e., degree of boosting) but also protects the turbine from possible damage. Interposed between the compressor and intake manifold, an intercooler is an auxiliary heat exchange device that cools down compressor air discharge before it reaches the intake manifold.[96] A concomitant pressure drop of compressed air circulating within the intercooler leads to denser air being transported to the intake manifold.
Cost	In new vehicles, the cost of turbocharging systems is inseparable from the vehicle cost which itself is strongly correlated to performance-related specifications such as volumetric displacement, top speed, range, acceleration, tailpipe emissions, and brand name as well. Thus, indicative costs of a 1,300 and 1,600cc vehicles fitted with direct injection technology lies between 19,000 and 22,000 Euros, with corresponding powertrain specific costs of 50.9 and 67.3 Euro/kW (Thiel et al, 2010). Assuming, a retrofit strategy is adopted by policy-makers/owners, the cost of a turbocharging unit approximates the market price of key component parts, and professional fees of engineer carrying out retrofit. At this point, a conservative estimate of direct injection retrofit cost falls within the range 850 to 1,800 Euros.
Supporting infrastructure	High quality roads
Advantages	Improves fuel economy of passenger vehicles by up to 30–50% (Saidur et al, 2012; Berggren and Magnusson, 2012) Enables engine downsizing without loss of performance (Jinnai et al., 2012)

---

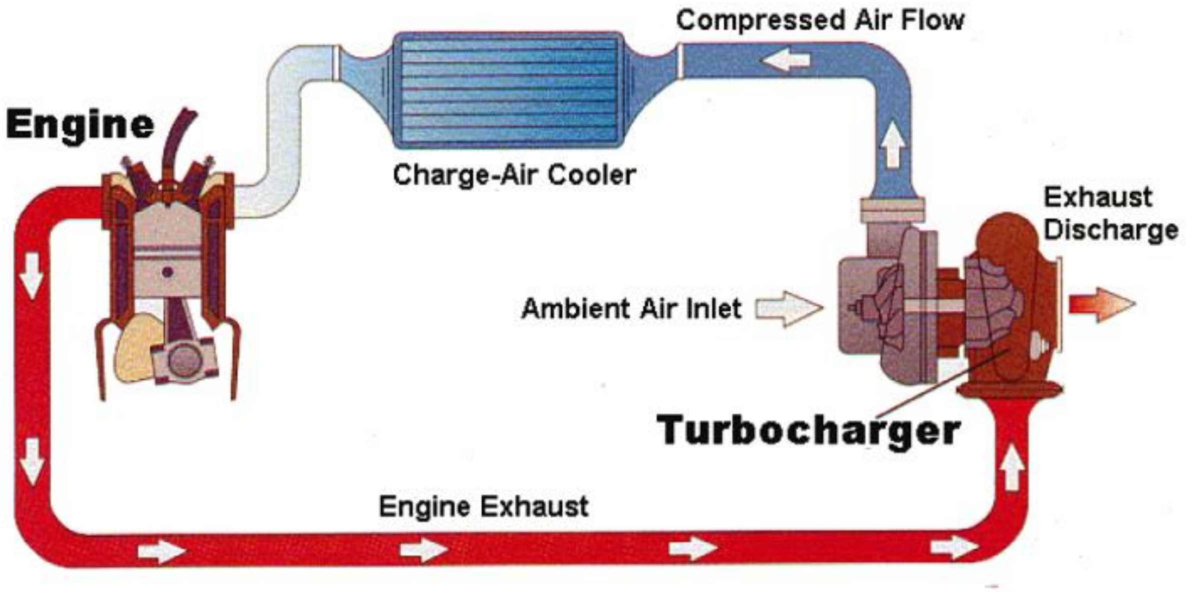
[93] In effect, pumping air under higher pressure into the combustion chamber proportionally increases the density of intake fuel-air mixture resulting in greater power generated per engine cycle, compared to naturally aspirated engines.

[94] Large turbochargers have higher inertia, creating lag at low speed. On the other hand, small turbochargers spin more quickly, but may not have the same performance at high acceleration. To this effect, complex configurations are sometimes deployed to take advantage of the performance characteristics of large and small wheeled turbines

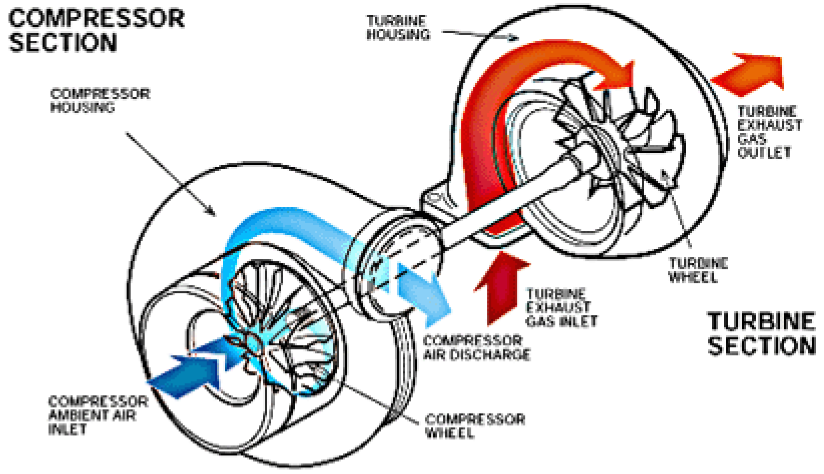
[95] The ECU directs various sub-systems of the vehicle by actuating certain key components and monitoring performance through a feedback from multiple sensors. In particular, it measures electric signals proportional to manifold air pressure during operation to determine dynamic response characteristics of the engine switch on/off the waste gate signal valve.

[96] The lowering of intake fuel-air mix temperature is a precaution taken against damage of engine components by overheating and pre-ignition. Air is also less dense, and contains less oxygen at higher temperature.

	Reduces particulates for diesel engines (Saidur et al, 2012) Low cost and high adaptability (Berggren and Magnusson (2012)
Disadvantages /Challenges	Poor transient response during low speed acceleration (Jinnai et al, 2012), although this shortcoming can be overcome by reducing the size of turbine and compressor wheels, or more revolutionary designs such as the variable geometry turbocharger, VGT (Saidur et al., 2012).
Abatement potential	Greenhouse emissions reduction attributable to fuel economy of turbocharged engine (Saidur et al, 2012; Jinnai et al., 2012) is mediated by a complex function of engine make, fuel type, fuel quality vehicle loads and driving patterns. CO_2 emissions reductions derived from literature range between 65 and 108gCO_2/km (Sullivan et al., 2004; Zhao et al. 1999).
Level of penetration	Unknown. Likely very small except for big cylinder motorcycles.



Source: http://www.marine-knowledge.com/wp-content/uploads/2013/10/Turbocharger-Working.png



Source: http://www.kadekticaret.com/turbo-parts.gif

Source:
http://www.vtrustcorporation.com/wordpress/wp-content/gallery/turbo-charger/compressor.jpg

Further Reading

Alkidas, A.C., 2007. Combustion advancements in gasoline engines. Energy Conversion and Management 48, 2751–2761

Berggren, B., Magnusson, T., 2012. Reducing automotive emissions—The potentials of combustion engine technologies and the power of policy. Energy Policy 41 (2012) 636–643

Galindo, J., Fajardo, P., Navarro, R., García-Cuevas, L.M., 2013. Characterization of a radial turbocharger turbine in pulsating flow by means of CFD and its application to engine modeling, Applied Energy 103 (2013) 116–127

Jinnai, Y., Arimizu, H., Tashiro, N., Tojo, M., Yokoyama, T., Hayashi, N., 2012. A variable geometry (VG) turbocharger for passenger cars to meet European Union emission regulations. Mitsubishi Heavy Industries Technical Review, Vol. 49 No. 2, 17 -26.

Saidur, R., Rezaei, M., Muzammil, W.K., Hassan, M.H., Paria, S., Hasanuzzaman, M., 2012. Technologies to recover exhaust heat from internal combustion engines. Renewable and Sustainable Energy Reviews 16 (2012) 5649–5659

Sullivan, J.L., Baker, R.E., Boyer, B.A., Hammerle, R.H., Kenny, T.E., Muniz, L., Waalington, T.J., 2004. CO_2 Emission Benefit of Diesel (versus Gasoline) Powered Vehicles. Environmental Science & Technology. Vol, 38, No. 12, 3217-3223

Thiel, C., Perujo, A., Mercier, A. 2010. Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios. Energy Policy 38, 7142–7151.

Uchida, H., 2006. Trend of turbocharging technologies. R&D Rev Toyota CRDL 2006;41(3):1–8
Zhao, F., Lai, M.C., Harrington, D.L., 1999. Automotive spark-ignited direct-injection gasoline engines. Progress in Energy and Combustion Science 25 (1999) 437–562

Websites

https://en.wikipedia.org/wiki/Turbocharger
http://auto.howstuffworks.com/turbo2.htm
https://en.wikipedia.org/wiki/Engine_control_unit

Battery-Powered Electric Vehicle (BPEV)

Defining characteristics	*Narrative*
General	Worldwide, most light- and heavy-duty road vehicles powered by internal combustion engines (ICEs) running on energy-dense fuels such as petrol, but a small proportion of the vehicle population operates on an entirely different principle, that is, the conversion of electrical energy to mechanical power. There are two primary options for all-electric vehicles: batteries or fuel cells with potential to substantially reduce the carbon footprint of the transport sector (Thomas, 2009). By design, a battery powered electric vehicle (BPEV) has no fuel tank or internal combustion engine (ICE) but derives all its power for propulsion from chemical energy stored in rechargeable battery packs. With environmental concerns gaining traction on the global policy agenda, and environmental regulations driving technological innovations on several fronts, automotive manufacturers are looking to electric propulsion as viable alternative to the ICE. Advances in battery technology in particular are addressing qualitative issues such as limited travel ranges that until recently confined BPEVs to niche applications such as urban transport and haulage within smoke-free environments (Kobayashi et al., 2009; Thomas, 2009). In many ways, BPEVs are making a comeback after being totally eclipsed by ICEs during the course of the past eight decades (Chan, 2007). Unlike lead acid batteries which primarily serve to start the engine and run accessories like the radio or air conditioners on ICE vehicles, the battery in a BPEV runs everything. The main benefits to a BPEV is lower operating cost arising from comparatively lower cost of electricity vis-à-vis refined fuels, and zero tailpipe emissions.
Siting and land use	Not relevant

Design (components) and Operation	Except for external features such as a charging port, BPEVs sold on today's automotive market have the same generic form, steering controls and appliances as ICE vehicles. Similarly, a BPEV uses a regenerative braking system to recharge a standard 12-volt battery when its brakes are applied, which battery powers the vehicle's auxiliary systems when its electric motor is not in use. Essentially, a functional BPEV has three distinctive components: 1) an energy storage unit; 2) a control unit; and 3) a propulsion unit. The energy storage unit is a high capacity chemical battery pack made from high energy density materials that store electricity and deliver it to the vehicle's onboard motor on-demand (Kobayashi et al., 2009). A control unit or controller provides intelligent energy management; regulating power and supplying either variable pulse width direct current (DC) or variable frequency and variable amplitude alternating current (AC), depending on the type of onboard motor and driving conditions. The controller also provides a mechanism for charging the batteries during deceleration, and a DC-to-DC converter to recharge the BPEV's 12-volt accessory battery. The propulsion unit comprising an electric motor and integrated power electronics converts electrical energy into mechanical energy that turns a drive ***axle*** transmitting full torque to the BPEV wheels. In some BPEV designs, electric motors[97] are installed inside wheels instead of a central position on the drive axle. When a BPEV contactor is switched on, electricity from the battery pack is fed to the controller which keeps track of accelerator pedal settings and sends power to the electric motor proportionate to a signal from potentiometers connected by cable to the accelerator pedal. Current from the battery is routed to the onboard motor by the controller with or without conversion into AC with an in-built set of transistors, depending on the type of electric motor installed. Inside the electric motor, current flows to a set of brushes that transmit current to a commutator connected to an armature coil and output shaft. Concomitantly, current flow from the controller energises a rotor coil which produces a rotating magnetic field. In their energised states, current in the armature interacts with the magnetic field producing a rotational motion of output shaft. To this effect, the more electric power the motor receives, the faster it can turn the drive ***axle*** that transmits power to the wheels. A dashboard display provides to a BPEV conductor with feedback on stored power dynamics and travel range of BPEV before battery recharge/swap is required.
Cost	The cost of BPEVs is related to many variables including primarily performance-related specifications such as travel range, top speed, power consumption, recharging time, and brand name as well. In general, BPEVs are more expensive than conventional ICE vehicles, but price differences are likely to narrow down as the technology gains maturity and market share. According to a comparative cost analysis of various propulsion systems, Thiel et al. (2010) report the cost of a BPEV powered by 80kW electric motor at around 35,000 Euro of which 14,400 Euro goes to cover the cost of a 24 volt lithium-ion (Li-ion) battery pack, corresponding to a battery specific cost of 600 Euro/kWh. In the same study, an electric motor costs up to 2,160 Euro, otherwise expressed as electric motor specific costs 27 Euro/kW. Working from an inventory of BPEVs in Perujo and Ciuffo (2010), the Subaru Stella model which has the lowest capacity and travel range[98] has a price tag of JPY 4,725,000

---

[97] There are four types of motors: synchronous, repulsion, universal, induction motors. Induction motors are more widely used because of their simplicity, low cost,, ruggedness, wide speed range and absence of back electromotive force (Chan, 2007)

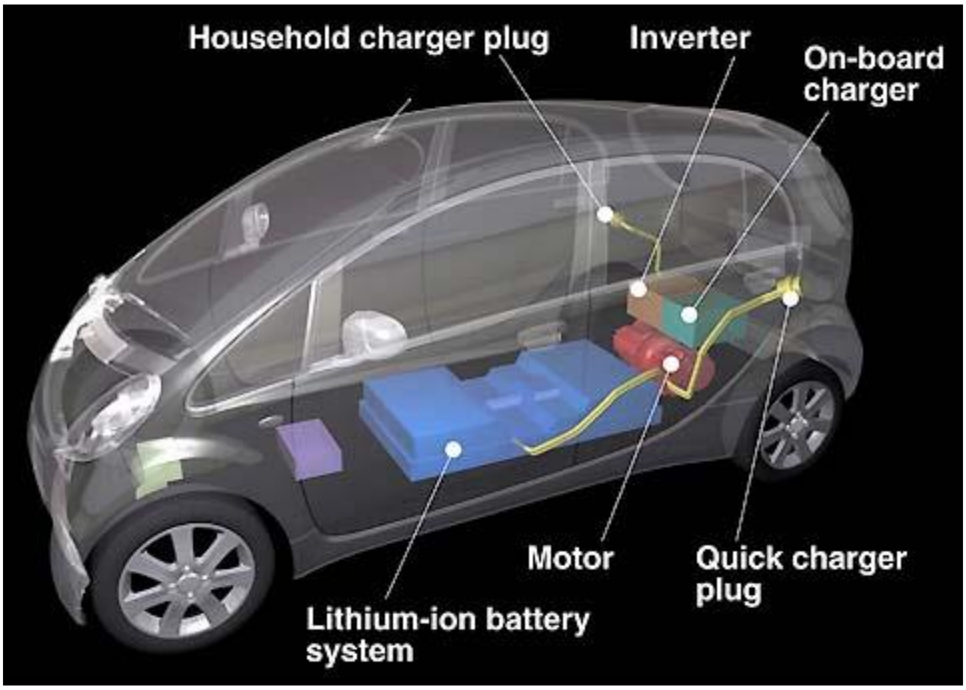
[98] Subaru Stella battery capacity = 9kW, travel range = 80 km

	(USD49,000), whilst the BYDe6 which features the highest capacity and travel range[99] costs USD50,000. Delucchi and Lipman (2001) report a retail price difference of USD3,000 to USD15,800 between a gasoline-powered Ford Taurus, and BPEVs using different battery packs. The authors found that lifecycle costs of approximately USD45,000 are considerably higher than comparable BPEV costs, except for some extensive range vehicles using nickel metal hydride (NiMH) batteries. Thomas (2010) citing an MIT study on the costs of various alternative vehicles, report that mass-produced BPEVs with ranges up to 320 km are likely to cost approximately USD10,200 more than conventional cars, one possible reason the Japanese government is offering a JPY1,380,000 (USD14,308) subsidy on the price of the Subaru Stella through its Next Generation Vehicle Promotion Center Program.[100]
Supporting infrastructure	Fuelling infrastructure High quality roads
Advantages	Higher energy efficiency compared to an ICE (Kobayashi et al., 2009) Few components (less maintenance requirements) Zero emissions Electricity generally cheaper than fuel oil Silent propulsion system (reducing noise pollution from traffic) Value for money with respect to FCEVs (Eaves and Eaves, 2004)
Disadvantages /Challenges	High initial cost Short battery life and high cost of batteries (Kobayashi et al., 2009) Short driving range (high recharging frequency) Exceedingly long battery recharge (power/fuel replenishment) times compared to other automotive technologies (Thomas, 2009) Requires recharging infrastructure analogous to refueling stations (Thomas, 2009)
Abatement potential	Greenhouse emissions reduction attributable to BPEVs is strongly correlated with the carbon intensity of the electricity generation infrastructure as wells as electric energy consumption of vehicles. The latter, specifically used in determinations of tank-to-wheel (TtW) GHG abatement, is dependent on a semi-finite set of BPEV motor efficiency and driving conditions. To fix some ideas, the TtW CO_2 abatement derived for the Subaru Stella electric vehicle with energy consumption of 11.25 kWh/100km is roughly 105gCO_2/km. Comparing well-to-wheel (WtW) CO_2 emissions 145gCO_2/km and 160gCO_2/km or higher for advanced diesel and gasoline vehicles respectively, with 60gCO_2/km for BPEVs, Thiel et al. (2010) concludes that the BPEV is the best automotive concept from a CO_2 WtW perspective, and is expected to maintain its advantage through 2030.
Level of penetration	Single digits

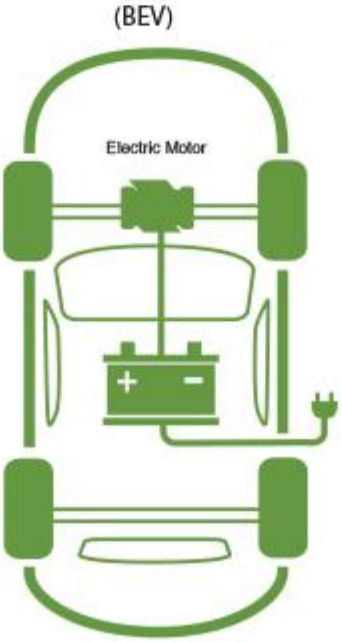
---

[99] BYDe6 battery capacity =72kW, travel range = 400km

[100] http://www.motorauthority.com/news/1033370_subaru-stella-electric-vehicle-goes-on-sale-in-japan



Source: http://exchangeev.aaa.com/wp-content/uploads/2012/09/battery_ev.jpg



Adapted from: https://www.sce.com/wps/wcm/connect/ef24e021-0fbc-4ed2-870a-55f6e5933623/LRM57_electric_vehicles_large.jpg?MOD=AJPERES&CACHEID=ef24e021-0fbc-4ed2-870a-55f6e5933623

Source:
https://s-media-cache-ak0.pinimg.com/564x/fb/46/bf/fb46bf9c5e9149fff448d0a4bf4adc15.jpg

Further Reading
Chan, CC., 2007. The state of the art of electric, hybrid, and fuel cell vehicles. Proceedings of the IEEE | Vol. 95, No. 4, 704 -718

Delucchi, M.A., Lipman, T.E., 2001. An analysis of the retail and lifecycle cots of battery-powered electric vehicles. Transportation Research Part D 6, 371 -404.

Eaves, S., Eaves, J., 2004.A cost comparison of fuel-cell and battery electric vehicles
Journal of Power Sources 130 (2004) 208–212.

Kobayashi S., Plotkin, S. Ribeiro, S.K., 2009. Energy efficiency technologies for road vehicles. Energy Efficiency 2:125–137. DOI 10.1007/s12053-008-9037-3

Perujo, A., Ciuffo, B., 2010. The introduction of electric vehicles in the private fleet: Potential impact on the electric supply system and on the environment. A case study for the Province of Milan, Italy Energy Policy 38 (2010) 4549–4561.

Thiel, C., Perujo, A., Mercier, A. 2010. Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios. Energy Policy 38, 7142–7151.

Thomas, C.E., 2009. Fuel cell and battery electric vehicles compared. International Journal of hydrogen energy, 34, 6005 – 6020.

Websites
https://en.wikipedia.org/wiki/Electric_motor
http://www.autoevolution.com/cars/subaru-stella-2006.html#aeng_subaru-stella-2006-07
http://www.caradvice.com.au/23826/2009-subaru-plug-in-stella-first-steer/
http://www.motorauthority.com/news/1033370_subaru-stella-electric-vehicle-goes-on-sale-in-japan
https://www.google.gm/?gws_rd=cr&ei=j2gxWK7eNsbDgAbc4aNg#q=byd+e6+price
http://www.byd.com/la/auto/e6.html
https://en.wikipedia.org/wiki/Engine_control_unit

Fuel Cell Electric Vehicle (FCEV)

Defining characteristics	*Narrative*
General	Worldwide, most light- and heavy-duty vehicles are powered by internal combustion engines (ICEs) that run on energy-dense fuels such as petrol, but a small proportion of the vehicle population operate on an entirely different principle, that is, the conversion of electrical energy to mechanical power. There are two primary options for all-electric vehicles: batteries or fuel cells with potential to substantially reduce the carbon footprint of the transport sector . By the nature of their electrochemical reaction, fuels cell can be more than twice as efficient as an ICE (Thomas, 2009). Major milestones in fuel cell technology[101] include their inaugural use in the US Apollo Space Program in the 1950s, and development of a working prototype of a fuel cell electric vehicle (FCEV) by General Motors in the mid-1960s. In decades since then, research and development (R&D) efforts, driven by climate change and energy security policy imperatives, have focused on addressing conversion efficiency, cost, cycle life and safety issues.. Today, hydrogen fuel cell electric vehicles (FCEVs) are recognised as being highly energy efficient and considered for their suitability as passenger and haulage vehicles in national road fleets. The main benefits to FCEVs are its competitive travel range, high energy efficiency and very low to zero tailpipe emissions (Kobayashi et al., 2009; Chan, 2007; Colella et al., 2005).
Siting and land use	Not relevant
Design (components) and Operation	Except for external features such as a charging port, FCEVs sold on today's automotive market have the same generic form, steering controls and appliances as ICE vehicles. Similarly, a FCEV uses a regenerative braking system to recharge a high capacity battery when its brakes are applied, which battery provides supplemental power when needed. Essentially, a functional FCEV has four distinctive components: 1) an energy storage unit; 2) a power generation unit; 3) a control unit; and 4) a propulsion unit. These work in synergy with reactant flow, heat and temperature control, and water management system components. An auxiliary battery provides supplemental power to motor during vehicle acceleration. The energy storage unit is a pressurised fuel tank for hydrogen, or other organic gases (methane or natural gas), or biofuels (methanol), which gases are converted by the power generation unit into electricity. The vehicle's onboard power generator unit is a fuel cell stack, made up of hundreds of fuel cells assembled together using bipolar plates that produces electricity, water and heat, directly from a fuel gas and an oxidant. The fuel cell stack is connected the FCEV's power control unit, supply and return lines from the fuel gas tank, an air supply, and external environment (Ahluwalia et al., 2004). A power control unit or controller provides intelligent energy management; regulating power and supplying either variable pulse width direct current (DC) or variable frequency and variable amplitude alternating current (AC), depending on the type of onboard motor and driving conditions. As power is continually drawn from the fuel cell stack to meet transient energy demands, the controller also receives and processes signals from the vehicle's reactant flow,[102] heat and temperature control,[103] water

---

[101] Fuel cells are devices that transform chemical energy encompassed within a fuel directly into electricity. Individual fuel cells which produce about 1 volt are connected in series to form a battery (of different shapes and sizes) for mobile or stationary applications.

[102] hydrogen and oxygen inlet and outlet flow rates

	management subsystems, thereby actuating corresponding pump and valve controls to satisfy performance, safety and reliability standards (Larminie and Dicks, 2003; Pukrushpan, 2003). The propulsion unit comprising an electric motor and integrated power electronics converts electrical energy into mechanical energy that turns a drive ***axle*** transmitting full torque to the FCEV wheels. In some FCEV designs, electric motors[104] are installed inside wheels instead of a central position on the drive axle. When a FCEV contactor is switched on, hydrogen from the pressurised storage tank(s) is inducted at the negative pole (anode) of the fuel cell where inflowing gas atoms are ionised with the help of a (platinum) catalyst, generating electricity in a circuit linking the negative and positive poles of the fuel cell, and water (vapour) and heat at the positive pole (cathode) of the fuel cell.[105] Excess/unused hydrogen is recycled to fuel tank(s) and water vapour evacuated through a tailpipe. Current from the fuel cell stack is routed to the onboard motor by the controller with or without conversion into AC with an in-built set of transistors, depending on the type of electric motor installed. Inside the electric motor, current flows to a set of brushes that transmit current to a commutator connected to an armature coil and output shaft. Concomitantly, current flow from the controller energises a rotor coil which produces a rotating magnetic field. In their energised states, current in the armature interacts with the magnetic field producing a rotational motion of output shaft. To this effect, the more electric power the motor receives, the faster it can turn the drive **axle** that transmits power to the wheels.
Cost	The cost of FCEVs is related to many variables including primarily performance-related specifications such as travel range, top speed, and power consumption. Brand names and production volume of this emerging technology also influences cost price. In general, FCEVs are more expensive than other vehicles, but price differences are likely to narrow down as the technology gains maturity and market share. Citing various studies, Eaves and Eaves (2009) report vehicle costs ranging between USD23,000 and USD29,000 for an FCEV delivering 100kW at peak power. Fuelling costs are estimated at USD1.00/kWh, 46% higher than that of battery-powered electric vehicles (BPEVs). However, these estimates appear outdated and over-optimistic. Toyota's Mirai, a 4-door sedan outfitted with a fuel cell-powered 113kW electric motor, with a first production run of 700 vehicles, is priced at JPY6.7 million (USD57,400) before expected Japanese government subsidy of JPY2 million (US$19,600) takes effect. In Germany, Germany starts significantly higher at €60,000 (US$75,140).[106] Honda's FCX Clarity powered 100kW electric motor sells for USD50,875.[107]

Oxygen required for a fuel cell comes from air that is pumped into the cathode to increase power generated. Larminie and Dicks (2003) show how hydrogen and oxygen flow rates can be determined analytically, enabling control over flow rates using advanced micro-processors.

[103] coolant flow rate and temperature

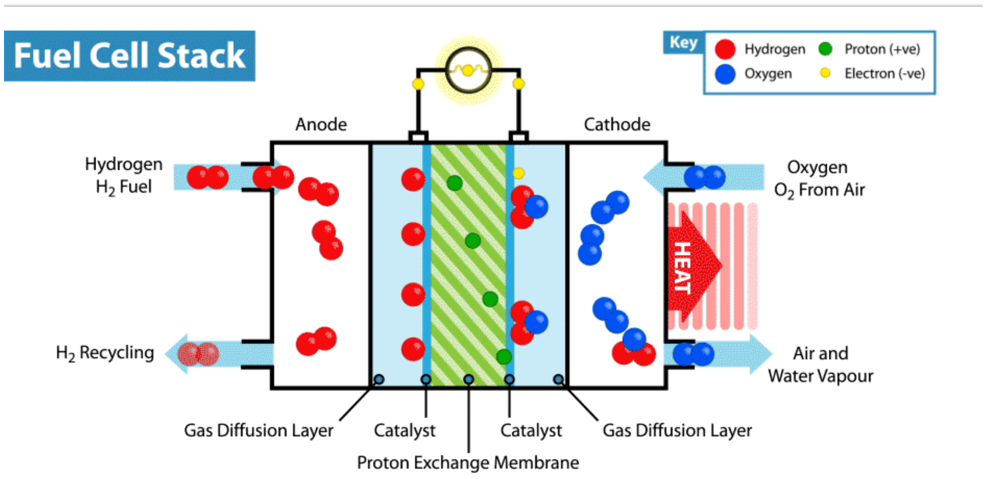
[104] There are four types of motors: synchronous, repulsion, universal, induction motors. Induction motors are more widely used because of their simplicity, low cost,, ruggedness, wide speed range and absence of back electromotive force (Chan, 2007)

[105] A fuel cell (FC) consists of an anode, a cathode and electrolyte sandwiched between the two. Its electrolytic proton exchange membrane acts as an electron barrier and proton carrier, forcing free electrons from H_2 to flow through a circuit from the anode to the cathode thus generating an electric current.

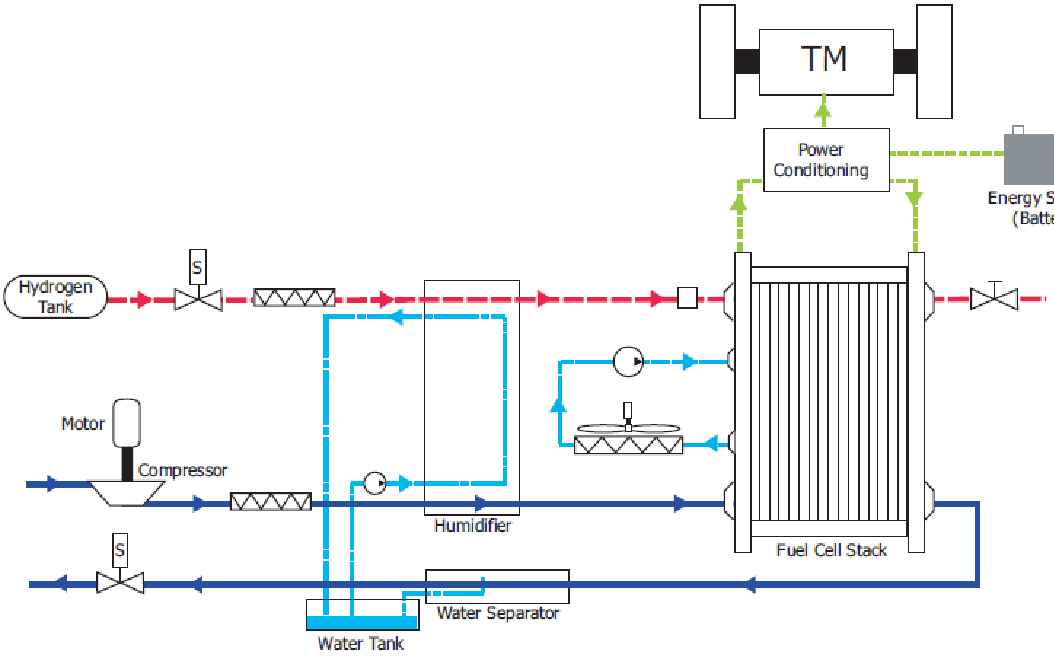
[106] https://en.wikipedia.org/wiki/Toyota_Mirai

[107] http://www.caranddriver.com/hyundai/tucson-fuel-cell

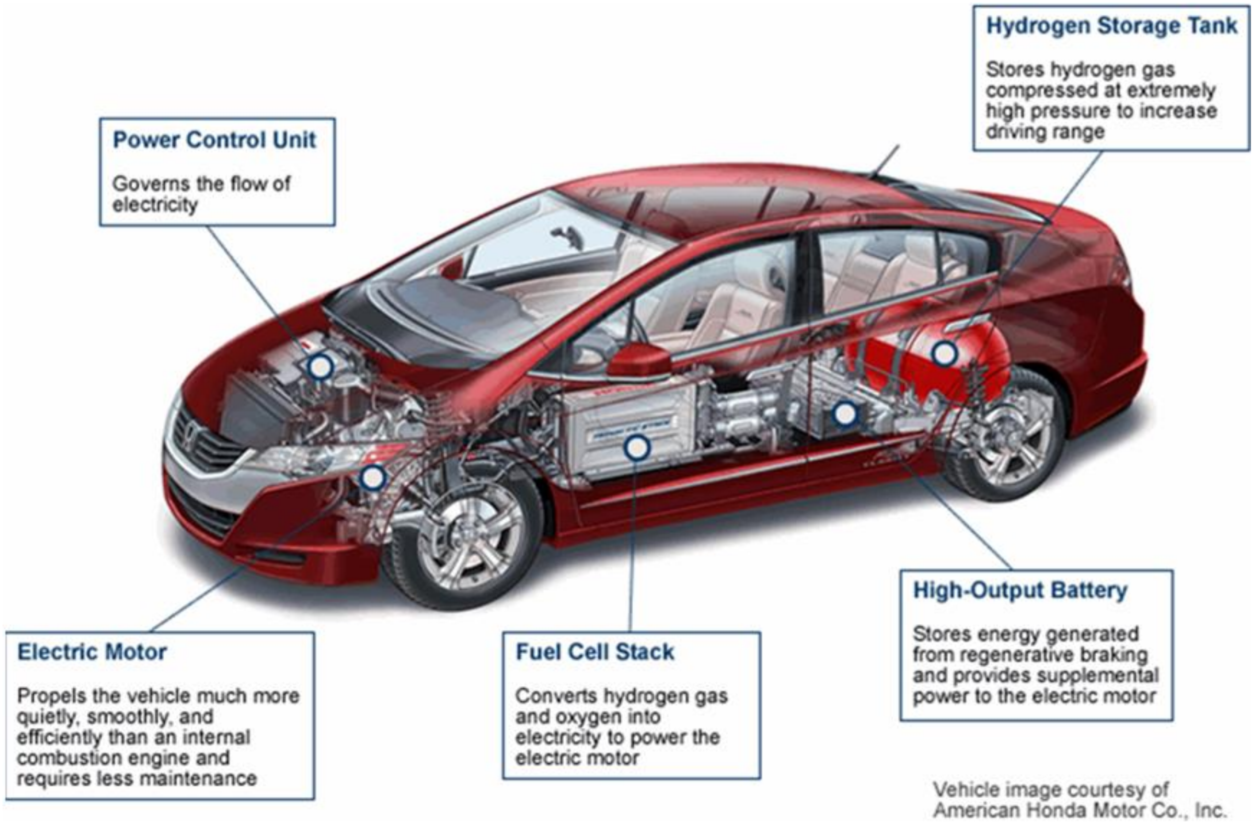
Supporting infrastructure	Fuelling infrastructure High quality roads
Advantages	High energy conversion efficiency compared to ICEs (Colella et al., 2005) Very low chemical and acoustical pollution (Chan, 2007) Fuel flexibility Rapid load response with satisfactory driving range
Disadvantages /Challenges	Initial and life-cycle costs with respect to conventional vehicles Underdeveloped hydrogen infrastructure (Thomas, 2009), although fuel processors currently under active development are capable of turning hydrocarbon or alcohol fuels into hydrogen, and consequently making this problem redundant FCV drivetrain costs remain at least an order of magnitude greater than internal combustion engine drivetrain costs (Kobayashi et al, 2009; Chan (2007)
Abatement potential	Depending on the primary source and production pathway of hydrogen used in FCEVs, Colella et al. (2005) report GHG and particulate emission reductions of 1 to 23% when hydrogen fuel is derived from coal and wind, respectively. Compared to ICE vehicles powered by gasoline, Kobayashi et al. (2009) report a 50 to 60% reduction in well-to-wheels (WtW) CO_2 emissions from FCEVs. Tank-to-wheel (TtW) emissions reduction is simply the foregone emissions by vehicles powered by internal combustion engines (ICEs) running.
Level of penetration	FCEVs are a completely new technology



Source: http://www.intelligent-energy.com/static/img/animations/fuel_cell_stack.gif



Source: Pukrushpan, J.T., 2003.



Source: http://www.intechopen.com/source/html/18666/media/image12.png

Source: https://www.youtube.com/watch?v=98EmzYK75QM

Further reading

Ahluwalia, R.K., Wang, X., Rousseau, A., Kumar, R, 2004. Fuel economy of hydrogen fuel cell vehicles. Journal of Power Sources, 130, 192 -201.

Colella, W.G., Jacobson, M.Z., Golden, D.M., 2005. Switching to a U.S. hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse gases. Journal of Power Sources, 150, 150–181.

Chan, CC., 2007. The state of the art of electric, hybrid, and fuel cell vehicles. Proceedings of the IEEE | Vol. 95, No. 4, 704 -718

Eaves, S., Eaves, J., 2004.A cost comparison of fuel-cell and battery electric vehicles
Journal of Power Sources 130 (2004) 208–212.

Kobayashi S., Plotkin, S. Ribeiro, S.K., 2009. Energy efficiency technologies for road vehicles. Energy Efficiency 2:125–137. DOI 10.1007/s12053-008-9037-3

Larminie, J., Dicks, A., 2003. Fuel cell systems explained. 2nd ed. John Wiley & Sons Ltd, Chichester, 389p+Appendices. Downloadable at: https://www.u-cursos.cl/usuario/c1f33623c53cd7f58fd77ef459693d6c/mi_blog/r/Fuel_Cell_Systems_Explained.pdf

Pukrushpan, J.T., 2003. Modeling and control of fuel cell systems and fuel processors. PhD dissertation, University of Michigan. Ann Arbor. Downloadable at: http://www-personal.umich.edu/~annastef/FuelCellPdf/pukrushpan_thesis.pdf

Thomas, C.E., 2009. Fuel cell and battery electric vehicles compared. International Journal of hydrogen energy, 34, 6005 – 6020

Websites

https://en.wikipedia.org/wiki/Electric_motor
http://www.intelligent-energy.com/technology/technology-faq/
https://en.wikipedia.org/wiki/Fuel_cell_vehicle
https://en.wikipedia.org/wiki/Powertrain_control_module

Annex II: List of stakeholders involved and their contacts

Table II.1 Contacts

Name	Affiliation	Designation	Phone	Email
Mr Momodou O. Njie	Ministry of Energy	Permanent Secretary	4466560	
Mr Lang Sabally	NAWEC	Corporate Services Director	3664007	
Mr Demba Jallow	NAWEC	Corporate Planning Manager	3664026	dembajallow@hotmail.com
Mr Ebrima Seckan	NAWEC	Water Distribution Manager	9964362	seckandemba@yahoo.com
Ms Haddy Jatou Njie	MOECCWFW	Administrative Assistant	7112511	njiehaddyjatou9@gmail.com
Mr Mass Njie	DOA	ICT Officer	9415744	mnjie2010@gmail.com
Mr Yaya Baldeh	DLS	M&E Officer	9224600	yayabaldeh61@hmail.com
Mr Njagga Touray	NEA	Senior Programme Officer	9293030	men2ray@gmail.com
Mr Olawale F. Olaniyan	ITC	Research Student	3701318	ofolanitan@hotmail.com
Mr Momodou Mendy	GTTI	Lecturer	9922892	mendymaa7@gmail.com
Mr Modou Dumbuya	MoWTI	Engineer	6871696	modoudumbuta1984@yahoo.com
Mr Amulie Jarjusey	MoWTI	Engineer	3914484	jarjuseyamulie@gmail.com
Mr Alpha Jallow	DWR	UNFCCC Focal Point	9725287	a_jallow2010@hotmail.com
Mr Ebou Mass Mbye	Fisheries Dept.	Principal Fisheries Officer	9944789	embye@gmail.com

Annex III: Details of MCA computations

Table III.1. Explanation of MCA Results

Criteria **Options**	**1**	**2**	**3**	**.**	**.**	**.**	**.**	**.**	**.**	**N**	**Weighted scores of each option**
Units Preferred value											
Weight	a_1	a_2	a_3	.	.	.	.	.	.	a_N	
Option 1	x_1	x_2	x_3	.	.	.	.	.	.	x_N	$\Sigma a_i x_i$
Option 2	y_1	y_2	y_3	.	.	.	.	.	.	y_N	$\Sigma a_i y_i$
Option 3	z_1	z_2	z_3	.	.	.	.	.	.	z_N	$\Sigma a_i z_i$

where: i = 1, 2, 3, ...N are numbers assigned to assessment criteria; a_i is the i-th criteria weight; x_i, y_i, z_i are scaled performance scores (0 to 100) of options 1, 2 and 3, with respect to the i-th criteria; and $\Sigma a_i x_i$, $\Sigma a_i y_i$, $\Sigma a_i z_i$ are weighted scores (0 to 100) computed for technology options 1, 2 an3 respectively

Table III.2. Energy Sector, Electricity subsector criteria weights and technology option scores - Base Case

Criteria **Options**	**Efficiency**	**Reliability**	**Cost**	**Land use**	**Acceptability**	**HR capacity**	**Safety**	**Durability**	**Noise**	**Emission**	**Employment**	**Weighted scores of each option**
Units	%	%	GMD	Ha	Ordinal	Ordinal	Ordinal	Years	dB	tCO/yr	Ordinal	
Preferred value	High	High	Low	Low	High	High	High	High	Low	Low	High	
Weight	8%	5%	25%	8%	12%	7%	9%	5%	4%	13%	4%	
Utility-Scale Solar PV	0.00	85.71	0.00	0.00	100.00	50.00	100.00	60.00	100.00	100.00	0.00	48.79
Wind Turbine	16.67	42.86	100.00	40.00	100.00	0.00	50.00	100.00	91.67	100.00	0.00	69.84
Tidal Stream Generator	0.00	0.00	65.00	0.00	0.00	0.00	0.00	0.00	75.00	100.00	50.00	34.25
Combined Cycle Diesel Generator	100.00	100.00	100.00	100.00	100.00	100.00	50.00	60.00	0.00	0.00	100.00	76.50

Table III.3 Energy Sector, Electricity subsector criteria weights and technology option scores - Sensitivity Analysis 1 of 2

Criteria Options	Efficiency	Reliability	Cost	Land use	Acceptability	HR capacity	Safety	Durability	Noise	Emission	Employment	Weighted scores of each option
Units	%	%	GMD	Ha	Ordinal	Ordinal	Ordinal	Years	dB	tCO/yr	Ordinal	
Preferred value	High	High	Low	Low	High	High	High	High	Low	Low	High	
Weight	10%	6%	25%	3%	13%	7%	12%	7%	2%	10%	5%	
Utility-Scale Solar PV	0.00	85.71	0.00	0.00	100.00	50.00	100.00	60.00	100.00	100.00	0.00	49.84
Wind Turbine	16.67	42.86	100.00	40.00	100.00	0.00	50.00	100.00	91.67	100.00	0.00	68.27
Tidal Stream Generator	0.00	0.00	65.00	0.00	0.00	0.00	0.00	0.00	75.00	100.00	50.00	30.25
Combined Cycle Diesel Generator	100.00	100.00	100.00	100.00	100.00	100.00	50.00	60.00	0.00	0.00	100.00	79.20

Table III.4 Energy sector, Electricity subsector criteria weights and technology option scores - Base Case - Sensitivity Analysis 2 of 2

Criteria Options	Efficiency	Reliability	Cost	Land use	Acceptability	HR capacity	Safety	Durability	Noise	Emission	Employment	Weighted scores of each option
Units	%	%	GMD	Ha	Ordinal	Ordinal	Ordinal	Years	dB	tCO/yr	Ordinal	
Preferred value	High	High	Low	Low	High	High	High	High	Low	Low	High	
Weight	10%	6%	30%	8%	7%	7%	6%	7%	4%	13%	2%	
Utility-Scale Solar PV	0.00	85.71	0.00	0.00	100.00	50.00	100.00	60.00	100.00	100.00	0.00	42.84
Wind Turbine	16.67	42.86	100.00	40.00	100.00	0.00	50.00	100.00	91.67	100.00	0.00	71.10
Tidal Stream Generator	0.00	0.00	65.00	0.00	0.00	0.00	0.00	0.00	75.00	100.00	50.00	36.50
Combined Cycle Diesel Generator	100.00	100.00	100.00	100.00	100.00	100.00	50.00	60.00	0.00	0.00	100.00	77.20

Table III.5 Transport Sector, Road transport subsector criteria weights and technology option scores - Base Case

Criteria **Options**	**Emissions**	**Safety**	**Noise**	**Fuel efficiency**	**Vehicle cost**	**Fuelling cost**	**Fuelling time**	**HR capacity**	**life span**	**Diffusion time**	**Weighted scores of each option**
Units	tCO2/year	Ordinal	dB	MPG-e/100 km	GMD	GMD/Gallon-e	minutes	Ordinal	years	years	
Preferred value	Low	High	Low	High	Low	Low	Low	High	High	Low	
Weight	18%	13%	7%	8%	11%	5%	9%	6%	11%	12%	
Direct fuel injection	66.67	33.33	50.00	100.00	100.00	0.00	100.00	100.00	0.00	100.00	65.83
Turbocharger	100.00	0.00	0.00	100.00	83.33	0.00	100.00	100.00	0.00	100.00	62.17
Fuel cell electric car	0.00	100.00	100.00	0.00	41.67	100.00	100.00	33.33	100.00	0.00	51.58
Battery-powered electric car	0.00	100.00	100.00	0.00	0.00	100.00	0.00	0.00	80.00	0.00	33.80

Table III.6 Transport Sector, Road transport subsector criteria weights and technology option scores - Sensitivity Analysis 1 of 1

Criteria **Options**	**Emissions**	**Safety**	**Noise**	**Fuel efficiency**	**Vehicle cost**	**Fuelling cost**	**Fuelling time**	**HR capacity**	**life span**	**Diffusion time**	**Weighted scores of each option**
Units	tCO2/year	Ordinal	dB	MPG-e/100 km	GMD	GMD/Gallon-e	minutes	Ordinal	years	years	
Preferred value	Low	High	Low	High	Low	Low	Low	High	High	Low	
Weight	18%	7%	7%	8%	19%	15%	3%	6%	11%	6%	
Direct fuel injection	66.67	33.33	50.00	100.00	100.00	0.00	100.00	100.00	0.00	100.00	59.83
Turbocharger	100.00	0.00	0.00	100.00	83.33	0.00	100.00	100.00	0.00	100.00	56.83
Fuel cell electric car	0.00	100.00	100.00	0.00	41.67	100.00	100.00	33.33	100.00	0.00	52.92
Battery-powered electric car	0.00	100.00	100.00	0.00	0.00	100.00	0.00	0.00	80.00	0.00	37.80

Table III.7 Waste Sector criteria weights and technology option scores - Base Case

Criteria Options	Feasibility	Investment cost	Operational cost	Versatility	Exclusion zone	Secondary output yield	Sustainability (feedstock)	Air pollution	Ground water pollution	Safety	Social benefit	Weighted scores of each option
Units	%	Ordinal	Ordinal	Ordinal	ha	%	Ordinal	Ordinal	Ordinal	Ordinal	Ordinal	
Preferred value	High	Low	Low	High	Low	High	High	Low	Low	High	High	
Weight	10%	10%	10%	5%	5%	5%	10%	15%	15%	10%	5%	
Sanitary landfill	80.00	0.00	0.00	100.00	0.00	75.00	100.00	100.00	100.00	100.00	100.00	71.75
Bioreactor landfill	80.00	0.00	0.00	100.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00	73.00
Anaeboric digester	40.00	50.00	100.00	50.00	50.00	62.50	50.00	50.00	0.00	50.00	50.00	47.13
Waste Incineration	60.00	0.00	0.00	100.00	100.00	25.00	50.00	0.00	100.00	50.00	0.00	42.25
Composting	100.00	100.00	100.00	0.00	50.00	87.50	0.00	100.00	0.00	100.00	50.00	64.38

Table III.8 Waste Sector criteria weights and technology option scores - Sensitivity Analysis 1 of 2

Criteria Options	Feasibility	Investment cost	Operational cost	Versatility	Exclusion zone	Secondary output yield	Sustainability (feedstock)	Air pollution	Ground water pollution	Safety	Social benefit	Weighted scores of each option
Units	%	Ordinal	Ordinal	Ordinal	ha	%	Ordinal	Ordinal	Ordinal	Ordinal	Ordinal	
Preferred value	High	Low	Low	High	Low	High	High	Low	Low	High	High	
Weight	10%	10%	10%	5%	5%	5%	10%	15%	15%	10%	5%	
Sanitary landfill	80.00	0.00	100.00	100.00	0.00	75.00	100.00	100.00	100.00	100.00	100.00	82.75
Bioreactor landfill	80.00	0.00	0.00	100.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00	79.00
Anaeboric digester	40.00	50.00	100.00	50.00	50.00	62.50	50.00	50.00	0.00	50.00	50.00	43.13
Waste Incineration	60.00	0.00	50.00	100.00	100.00	25.00	50.00	0.00	100.00	50.00	0.00	50.75
Composting	100.00	100.00	100.00	0.00	50.00	87.50	0.00	100.00	0.00	100.00	50.00	59.88

Table III.9 Waste Sector criteria weights and technology option scores - Sensitivity Analysis 2 of 2

Criteria **Options**	**Feasibility**	**Investment cost**	**Operational cost**	**Versatility**	**Exclusion zone**	**Secondary output yield**	**Sustainability (feedstock)**	**Air pollution**	**Ground water pollution**	**Safety**	**Social benefit**	**Weighted scores of each option**
Units	%	Ordinal	Ordinal	Ordinal	ha	%	Ordinal	Ordinal	Ordinal	Ordinal	Ordinal	
Preferred value	High	Low	Low	High	Low	High	High	Low	Low	High	High	
Weight	10%	10%	10%	5%	5%	5%	10%	15%	15%	10%	5%	
Sanitary landfill	80.00	0.00	100.00	100.00	0.00	75.00	100.00	100.00	100.00	100.00	100.00	80.75
Bioreactor landfill	80.00	0.00	0.00	100.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00	67.00
Anaeboric digester	40.00	50.00	100.00	50.00	50.00	62.50	50.00	50.00	0.00	50.00	50.00	51.13
Waste Incineration	60.00	0.00	50.00	100.00	100.00	25.00	50.00	0.00	100.00	50.00	0.00	43.75
Composting	100.00	100.00	100.00	0.00	50.00	87.50	0.00	100.00	0.00	100.00	50.00	68.88