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Assessing the water-energy-carbon nexus for water supply in the Mgeni system using a water balance approach

V Nagan, M Seyam

In the 21st century emphasis has been placed on carbon footprint reduction and a net-zero future. As a water-scarce country, South Africa will face significant water deficits in almost all areas of water management by 2025 (Gebrehiwot & Gebrewahid 2016). Efforts are being made by water service authorities to increase potable water production to cope with increasing population and climate change. In the Umgeni-uThukela water supply system, Mgeni accounts for approximately 80% of the total water supply volume. One of the major concerns in water production is the energy usage and its resulting carbon emissions. The Mgeni system uses approximately 195 795 MWh of energy to produce the water demand for the system. Carbon accounting plays a critical role in ensuring that South Africa meets its international climate change commitments. This study utilised the National Generation Grid Emission Factor (NGGEF), as stipulated in South Africa's 2021 Grid Emission Factors Report (DFFE 2024)

The objectives of this study was therefore to: (a) determine the water balance for the Mgeni system, (b) assess the energy usage projection and determine the carbon emissions generated using a carbon balance approach, and (c) determine the future carbon reduction of water losses.

The water supply system was analysed using the IWA Standard Water Balance Method, and water losses were determined from the water balance. Further carbon calculations were conducted using the IWA Standard Carbon Balance (Leakage Emissions Initiative). The analysis indicated that the water supplied to the system (SIV) increases from 396 million m^3/annum to 510 million m^3/annum, while the water losses equate to approximately 133 million m^3/annum to 250 million m^3/annum.

The carbon emissions from majority coal energy generation were approximately 438 526 tCO_2/year in 2018, and were shown in this study to increase to 2 703 060 tCO_2/year in 2050. With the reduction of water losses, this could decrease by about 18–25%. The carbon emissions produced by renewable energy generation were approximately 333 781 tCO_2/year in 2018, with an expected increase to 1 191 831 tCO_2/year in 2050.

A global study on water distribution systems determined that implementing pressure management could reduce water losses by 38% which ultimately reduces energy consumption by 20–40% (Danfoss 2018). Furthermore, implementation of active leak detection could reduce water losses from leakages by 50%, which would result in reduction in energy consumption and carbon emissions (Ong *et al* 2023). The water industry must play its part and reduce its greenhouse gas footprint. To achieve net-zero carbon emissions from water production activities, water conservation and demand management strategies, such as pressure management and active leak detection, must be introduced to reduce water losses, thereby reducing energy usage and carbon emissions.

Keywords: water management, carbon emissions, water losses, water balance, carbon balance



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INTRODUCTION

Leading Africa in greenhouse gas (GHG) emissions, South Africa has committed to move towards a low-carbon economy and net-zero future that addresses the broader impacts of climate change (Lee & Baumgartner 2020). Water in South Africa has a powerful link not only to all aspects

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of the physical environment, but also to poverty reduction, sustainability, equity, and economic development (Knight & Rogerson 2019).

South Africa is amongst the world's most carbon-intensive economies (Alton *et al* 2014). Although the Department of Water and Sanitation (DWS) implemented water conservation and demand management (WC/DM) strategies, the demand continues to increase. Instead of merely concentrating on expanding the supply of freshwater, South Africa must also pay attention to minimising water use. South Africa therefore needs to focus clearly on the need to reduce water demand, and not just on increasing freshwater supply. The way forward to proper water resource management lies in effective demand management approaches to the resource (Jacobs-Mata *et al* 2018).

The water-energy-carbon nexus refers to the interaction between water management, energy consumption and CO_2 emissions caused by water management resources. In order to achieve sustainability and address global challenges, such as climate change, focus needs to be on balancing water availability, optimising energy use, and minimising carbon emissions. The water-energy-carbon nexus can be effectively managed to reduce usage of water and energy, lower carbon emissions, and promote sustainable development. Identifying and addressing the connections between water, energy and carbon can help societies better navigate the challenges posed by climate change, resource scarcity, and increasing demands.

The Mgeni system is crucial to the economic development, industrial development, and agriculture of the KwaZulu-Natal Province. In addition to ensuring adequate water supply for the region, efficient management of the Mgeni system is essential for the region's economy, environment, and community development. Umgeni Water provides potable water to seven Water Service Authorities (WSAs) within the KwaZulu-Natal Province, which equates to 509 million cubic metres of potable water per annum. This study focused mainly on the Mgeni system, which consists of the Upper and Lower Mgeni systems. The Upper Mgeni system supplies potable water to the uMgungundlovu District Municipality, Msunduzi Municipality, and the eThekwini Municipality Outer West area, while the Lower Mgeni system supplies potable water to the coastal areas and the hinterland of the eThekwini Municipality (Umgeni Water 2020).

Many Water Service Authorities encounter excessive water losses, accounting for about 35% of the total supply volume (Umgeni Water 2020). Non-Revenue Water (NRW) is the volume of water produced and distributed by a utility which does not generate revenue to the utility. NRW can be regarded as the real and apparent losses which occur from leaks, burst pipes, theft, meter reading errors, etc. The national average NRW for South Africa is about 35%, while, in comparison, the international NRW ranges between 5% and 15%. Some communities have NRW much higher than the national average. Typical examples include the Mbombela Local Municipality (40–70%) and the Emfuleni Local Municipality (49%) (Mutamba 2014).

Carbon accounting plays a critical role in ensuring that South Africa meets its international climate change commitments. South Africa's National Climate Change Response Policy (NCCRP) of 2011 cites the need for accurate, complete and up-to-date data as the foundation of an effective climate change response (DFFE 2024). The carbon emissions are determined using the National Generation Grid Emission Factor (NGGEF) methodology to quantify the level of carbon emissions.

This study investigated the effectiveness of reducing water losses in the combat to reduce carbon emissions in the water supply environment. The study area (being the Mgeni system which mainly services the Durban and Pietermaritzburg areas) has seen an increase in population growth of 1.1% per annum, putting severe strain on the water industry, which as a result has seen an increase in carbon emissions. Durban and Pietermaritzburg are regarded as the economic hubs of the KwaZulu-Natal Province, hence the vast increase in population within the area. As a result, the Water Service Authority has to implement effective measures to conserve water and manage water supply and demand to ensure the security of water supply and to make progress in the net-zero carbon initiatives.

The objective of this research was achieved through the following specific procedures:

a. Determine the water balance for the Mgeni system.
b. Assess the energy usage projection for the Mgeni system and determine the carbon emissions generated using a carbon balance approach.
c. Determine the future carbon balance by considering reduction in water losses.

It is hoped that the outcomes of this study will provide more insight into carbon emissions generated from water supply at an end-user assessment. Results from the study should form a basis for an understanding of carbon emissions generated from such activity, thereby enabling effective planning for water distribution, management, and conservation to sustain the scarce resource.

MATERIALS AND METHODS

Study area

The study was carried out in the Pongola-Mtavuna water management area, consisting of the Thukela (V) and Mvoti-Umzinkuklu (U) primary catchment. The study focused on the Mgeni system which consists of the Upper and Lower Mgeni systems managed by Umgeni-uThukela Water, the main supplier of potable water to most of the KwaZulu-Natal Province. The Mgeni system is recognised as the main source of water supply to the Durban and Pietermaritzburg region. As the Durban-Pietermaritzburg region is the primary economic hub of KwaZulu-Natal, a high level of demographical pressure and water supply problems can be expected. The study area consisted of three municipalities, namely eThekwini, Msunduzi and uMgungundlovu Municipalities, as shown in Figure 1.

Background to water supply

Umgeni-uThukela Water provides potable water to seven Water Service Authorities (WSAs) within the KwaZulu-Natal area, which equates to approximately 509 million m^3 of potable water per annum. The Mgeni system is serviced by the Mooi River and the Mgeni River. The system operates through gravity systems (shown in blue lines in Figure 2) from the Midmar, Inanda, Nagle and Albert Falls Dams. The operating rule maximises the reliability of supply in the system through pumping (shown in red lines in Figure 2) from Spring Grove Dam, Mearns Weir (Mooi River) and Inanda Dam to reduce the risk of drought water restrictions as far as possible. The current operating rule for the Mgeni system, as shown in Figure 2, optimises the assurance of supply via all the pumping

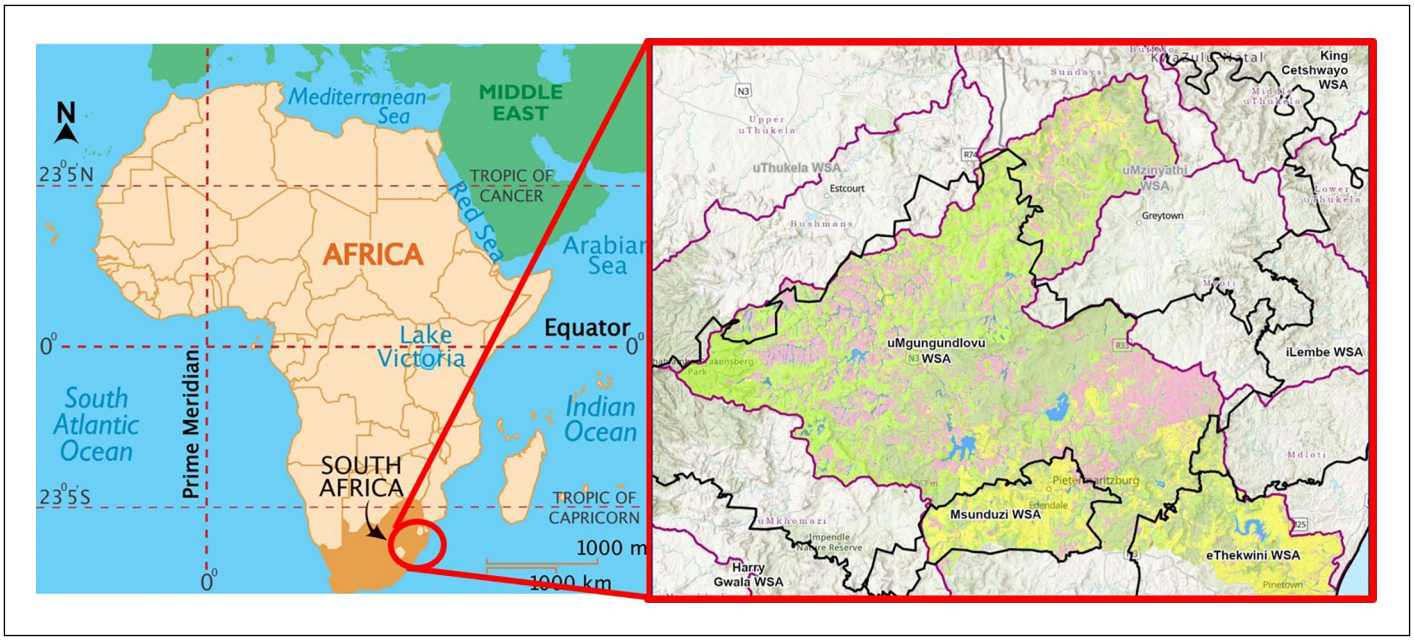


Figure 1 Location of the study area

that is undertaken simply because the water requirements are now higher than the long-term yield. Pietermaritzburg is serviced by the Midmar and DV Harris Waterworks, while Durban is serviced by the Durban Heights and Wiggins Waterworks (Umgeni Water 2020).

The three WSAs being studied are the eThekwini Municipality, Msunduzi Municipality, and uMgungundlovu District Municipality. These WSAs are described in detail below:

a. The eThekwini Municipality is primarily supported by the Mooi-Mgeni transfer scheme. Water in the eThekwini Municipality's northern areas is also secured from the Hazelmere Dam on the Mdloti River and from the Tongati River. The Nungwane Dam on the Nungwane River provides a small portion of the municipality's water requirements in its southern areas. Groundwater is also used to a limited extent. Water transfers from the uMkhomazi River; wastewater reuse and seawater desalination are potential future water sources for this area. Water from the uThukela River could also be utilised to a limited extent (Umgeni Water 2016).
b. The Msunduzi Municipality is only supported by the Midmar Dam on the Mgeni River. Water transfers from the Mooi River are used to augment this resource. Groundwater is used to a limited extent (Umgeni Water 2016).
c. The uMgungundlovu District Municipality is primarily supported by the Midmar Dam on the Mgeni River, supported by the Mooi-Mgeni transfer scheme, which is the primary source of water for this municipality (Umgeni Water 2016).

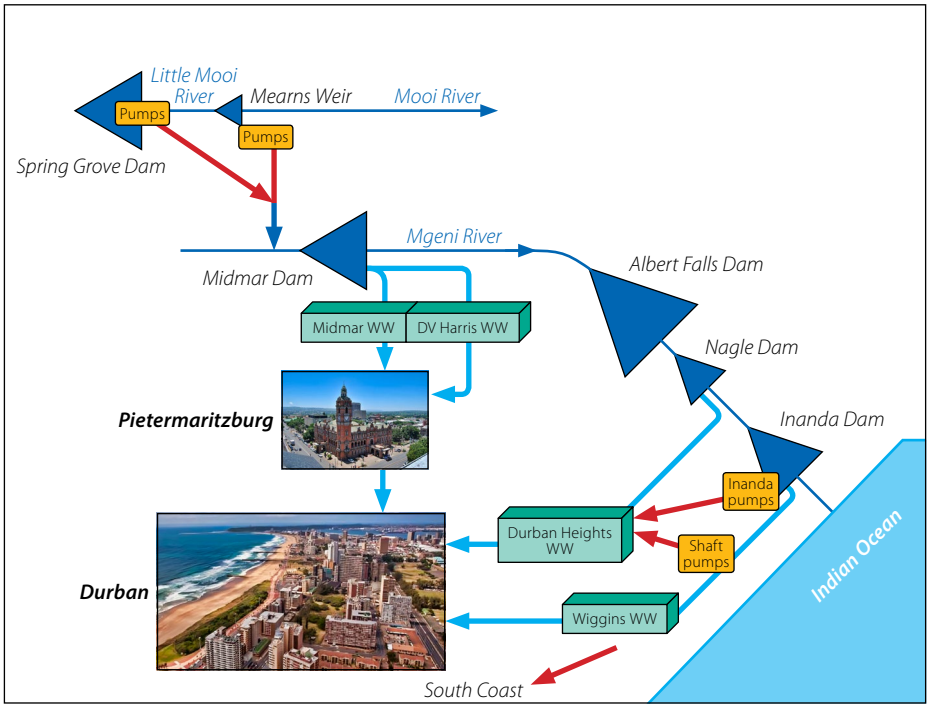


Figure 2 Mgeni system infrastructure configuration (Umgeni Water 2020)

Data collection

The study of carbon emissions in water supply systems is a crucial aspect of understanding the impacts of the water industry on achieving the Sustainable Development Goals (SDGs). This research considered the energy requirements for municipalities in the study, which included all its treatments and processes. Data obtained for this analysis were obtained from the sources shown in Table 1.

Methodology

Three main approaches are used to calculate carbon emissions. These are the top-down, bottom-up, and hybrid approaches (Ercin & Hoekstra 2012).

- In the top-down approach, emissions are estimated based on aggregated, macro-level data, and depend on data from economic and sectoral statistics and satellites to determine associated carbon emissions.
- In the bottom-up approach, emissions are calculated based on more localised information where emissions data

Table 1 Description and sources of data used

Data	Description	Source
Carbon intensity	Carbon intensity value	South Africa's 2021 Grid Emission Factors Report (DFFE 2024)
Projected water demands (period 2018 to 2050)	Water demand requirements for the study area	Umgeni Water Infrastructure Master Plan 2023 (Umgeni Water 2023a)
Municipal water losses	Water losses per municipality	Umgeni Water Infrastructure Master Plan 2020 (Umgeni Water 2020)
Energy consumption	Electricity consumption for water supply	Umgeni Water Infrastructure Master Plan 2020 (Umgeni Water 2020)
Water balance components (i.e. SIV, losses, billed meter, etc)	Water balance data for the study area	The Status of Non-Revenue Water in the Province of Kwazulu-Natal as of end of the 2022/23 Financial Year (Umgeni Water 2023b)

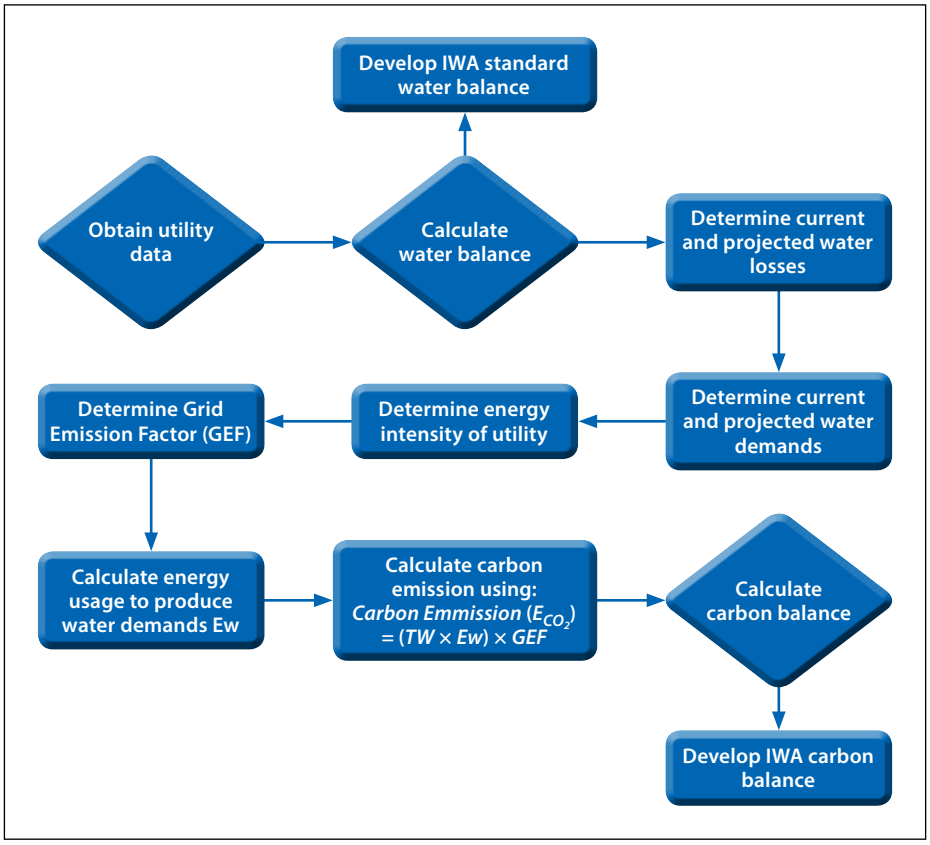


Figure 3 Research methodology in assessing the water and carbon balance

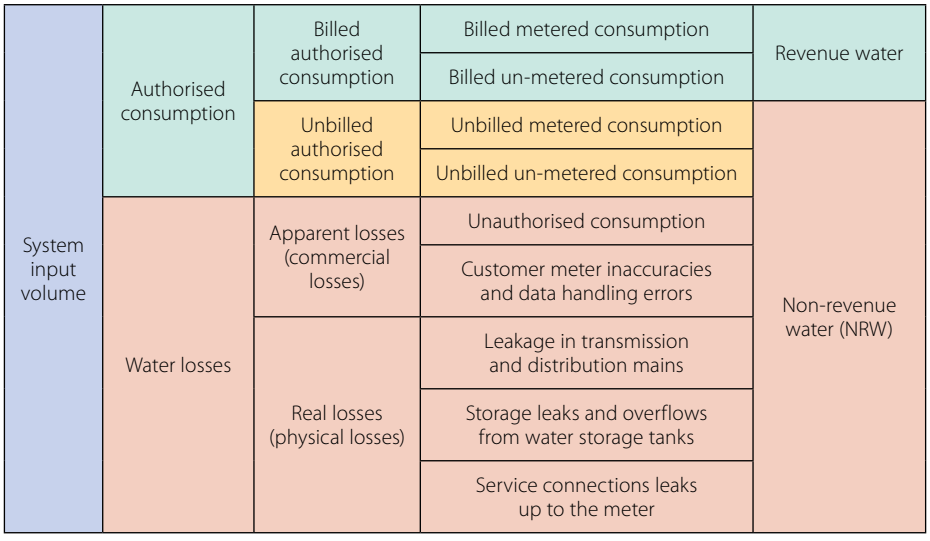


Figure 4 IWA water balance (McKenzie *et al* 2007)

is collected directly from individual sources such as water authorities.
- The hybrid approach to determining carbon emissions combines both top-down and bottom-up methods.

This study focused on the bottom-up approach as it determines the carbon emissions for the Mgeni system at a local level using historical data to project future carbon emissions. Figure 3 provides an illustration of the methodology used in this study.

IWA Standard Water Balance

The International Water Association (IWA) Water Balance is used as a graphical tool worldwide to quantify volumes of water that enter the system, and shows the amount of authorised consumption and water losses in the system. It also highlights the non-revenue water and the revenue water to illustrate the economics of the system. Figure 4 shows the breakdown of the IWA Water Balance (McKenzie *et al* 2007).

Water loss is an important indicator of how much water is currently being used within an area and utility. In spite of the best operation and maintenance, water losses cannot be eliminated completely. The characteristics of the water supply systems can be measured based on a variety of key performance indicators (KPIs) once the water balance has been determined. In order to improve efficiency and reduce commercial losses, physical losses, or NRW, the water utility needs to determine the water balance, as well as KPIs. Identifying and quantifying the main sources of water loss contribute to identifying the most effective WC/DM intervention to eliminate them. Non-Revenue Water (NRW) comprises the following categories:

- unbilled metered
- unbilled un-metered
- illegal connections
- inaccurate meters
- mains leaks
- reservoir overflows
- service connection leaks.

Definitions of the principal components shown in Figure 4 are as follows (Wegelin 2015):

a. System Input Volume: the annual input to a defined part of the water supply system.
b. Authorised Consumption: the annual volume of metered and/or non-metered water taken by registered customers.

c. Non-Revenue Water (NRW): the difference between system input volume and authorised consumption.
d. Apparent Losses: these comprise unauthorised consumption and metering inaccuracies.
e. Real Losses: the annual volumes lost through all types of leaks, bursts and overflows on mains, etc.
f. Billed Unmetered Consumption: volume of water for which a bill is issued by the utility. This can refer to deemed consumption and/or free basic water.
g. Billed Metered Consumption: water connection fitted with a meter and linked to a customer account which is billed.
h. Unbilled Metered Consumption: volume of water used for municipal parks, road islands, firefighting, municipal gardens and public facilities.
i. Unbilled Unmetered Consumption: volume of water used for flushing of mains and maintenance of water infrastructure.

The IWA Standard Water Balance has been developed and utilised globally. However, South Africa has modified the IWA Standard Water Balance to allow for the regulation of free basic water. The modified IWA Standard Water Balance is shown in Figure 5.

<table>
<tr><td rowspan="8">System input volume</td><td rowspan="4">Authorised consumption</td><td rowspan="2">Billed authorised consumption</td><td>Billed metered consumption</td><td>Free basic water</td></tr>
<tr><td>Billed un-metered consumption</td><td>Revenue water</td></tr>
<tr><td rowspan="2">Unbilled authorised consumption</td><td>Unbilled metered consumption</td><td rowspan="6">Non-revenue water (NRW)</td></tr>
<tr><td>Unbilled un-metered consumption</td></tr>
<tr><td rowspan="4">Water losses</td><td rowspan="2">Apparent losses (commercial losses)</td><td>Unauthorised consumption</td></tr>
<tr><td>Customer meter inaccuracies and data handling errors</td></tr>
<tr><td rowspan="3">Real losses (physical losses)</td><td>Leakage in transmission and distribution mains</td></tr>
<tr><td>Storage leaks and overflows from water storage tanks</td></tr>
<tr><td>Service connections leaks up to the meter</td></tr>
</table>

Figure 5 Modified water balance (Wegelin *et al* 2014)

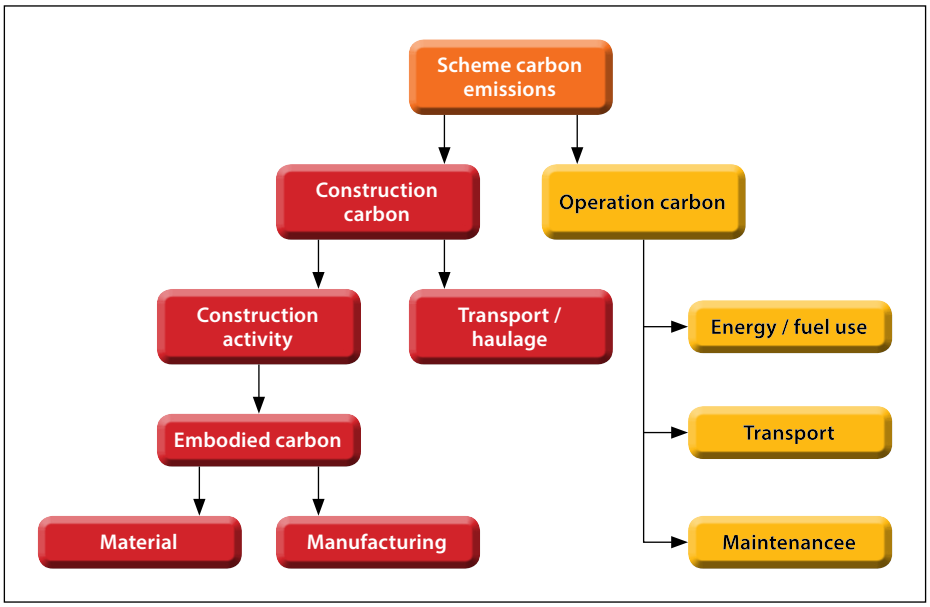


Figure 6 Carbon footprint for a water supply scheme in construction and operation (Reffold *et al* 2008)

IWA Standard Carbon Balance (Leakage Emissions Initiative)

Carbon emissions consist of construction carbon and operational carbon. Many organisations focus on construction carbon and reducing the carbon produced during activities such as construction of infrastructure, transport movement during construction and manufacturing of construction materials. However, focus should be more on operational carbon and reducing carbon during operational activities, such as the heating and cooling of buildings, pumping, etc. Figure 6 illustrates the difference between operational and construction carbon. One way of reducing operational carbon in the water industry is by deploying affordable and high-efficiency technologies and by retrofitting existing systems through the implementation of water-saving equipment.

The International Water Association (IWA) has published and developed a Standard Carbon Balance for water utilities to assess the carbon generated from water supply. The purpose of this carbon balance is to quantify the amount of carbon attributed to sources, uses, and losses (including leakage) for a given utility. The balance is intended to incentivise utilities to aggressively identify and reduce leakage, generating carbon credits which can then be sold to organisations seeking to achieve carbon neutrality (Hamilton *et al* 2023). Carbon emissions can be determined using Equation 1.

$$\text{Carbon Emission } (E_{CO_2}) = TW \times GEF \quad (1)$$

Where:
Carbon Emission (E_{CO_2}) = CO_2 Emissions for X year (tCO_2/year)
TW = Total Water Volume for X year (m^3/year)
GEF = Grid Emission Factor for electricity production (tCO_2/KWh).

Equation 1 can be derived to accommodate energy usage into the formula as follows:

$$\text{Carbon Emission } (E_{CO_2}) = (TW \times Ew) \times GEF \quad (2)$$

Where:
Carbon Emission (E_{CO_2}) = CO_2 Emissions for X year (tCO_2/year)
Ew = Energy Usage Factor to produce potable water (KWh/m^3)
GEF = Grid Emission Factor for electricity production (tCO_2/KWh).

The IWA Standard Carbon Balance utilises the IWA International Standard Water Balance and quantifies the amount of carbon attributed to each of those same sources, uses, and losses (including leakage) for a given utility.

Total water supply projections

The first step in a carbon initiative involves calculating or assessing the carbon footprint

Table 2 Population growth (Umgeni Water 2020)

	Population (person)				
	2009	2016	2018	2019	Average % growth
eThekwini	3 442 070	3 702 231	3 784 128	3 825 754	1.1
uMgungundlovu	409 237	416 826	426 047	430 733	1.1
Msunduzi	606 888	679 039	694 060	701 695	1.1
Total	4 458 195	4 798 096	4 904 235	4 958 182	1.1

Table 3 Historical water demand for the Mgeni system (Umgeni Water 2023b)

	2009	2015	2016	2018	2019
eThekwini (Ml/d)	565	894	840	938	992
uMgungundlovu (Ml/d)	44	54	57	61	69
Msunduzi (Ml/d)	116	192	171	196	203
Total (Ml/d)	725	1 140	1 068	1 195	1 264

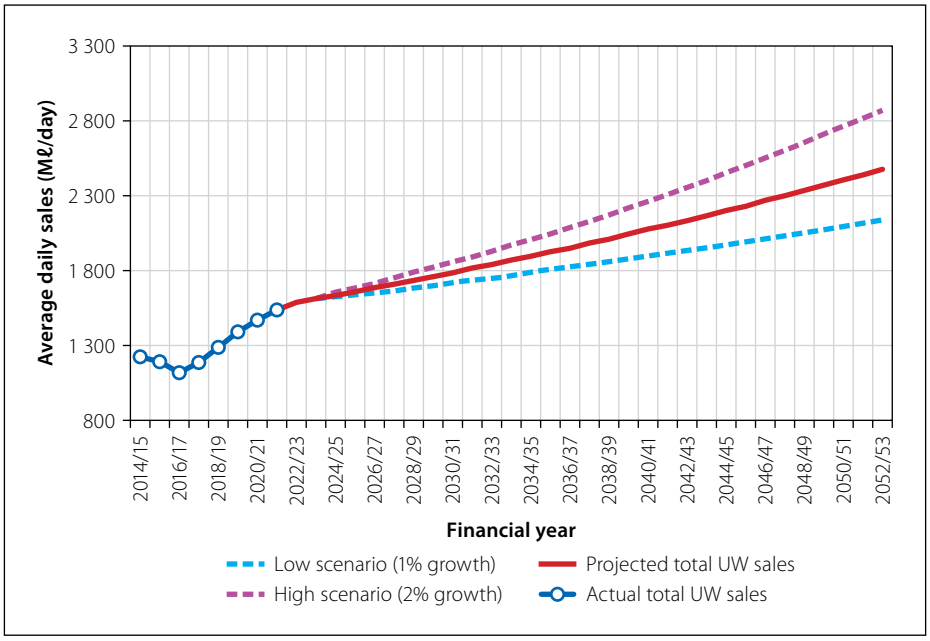


Figure 7 Projected water demand for the Mgeni system (Umgeni Water 2023a)

of the water utility. This involves quantifying the amount of greenhouse gas emissions produced, measured in terms of carbon dioxide equivalents (CO_2e) (Hamilton and Charalambous 2024). The Mgeni system has an exponential increase in water demand, which is based on the current population growth of 1.1% per annum, as shown in Table 2 (Umgeni Water 2020).

Historical water demands, as shown in Table 3, have been determined from *The Status of Non-Revenue Water in The Province of KwaZulu-Natal as of End of the 2022/23 Financial Year* (Umgeni 2023b).

The water demand projections for the study period are illustrated in Figure 7 (Umgeni Water 2023a). It can be seen that due to demographical pressure, the water supply increases exponentially from 2018 to 2050. In order to meet the water demands for the area, a vast amount of electricity is being used to treat raw water to potable water. This research used the current and projected water demand to determine a carbon emission forecast. Further water loss reduction estimations will be determined and analysed to determine the carbon emission reductions.

For the 2021/2022 financial year, Mgeni system accounted for water consumption being 81.99% and the power usage being 74.87% of total power usage throughout the Umgeni-Thukela Water supply area (Umgeni Water 2023a).

Total water losses

It is imperative that all South Africans understand the importance of conserving the nation's water resources in order to ensure the effectiveness of water conservation and demand management programmes. There are traditional stereotypes and mindsets that lead to high water usage, including the belief that water is abundant and freely available (DWS 2018).

Water losses are grouped into two types – real losses and apparent losses. Whilst real losses are an expense due to lost water, apparent losses are not so much an expense to the water utility as it poses a loss of revenue. In order to resolve the water losses within the system, one needs to understand the terminology of water losses and how it originates. The International Water Association defines water loss as:

$$\text{WL (water losses)} = \text{RL (real losses)} + \text{AL (apparent losses)} \quad (3)$$

The management of real losses in water distribution systems typically revolves around the following four key pillars (often referred to as the *Four Pillars of Real Losses*):

- pressure management
- speed and quality of repairs
- active leakage control
- infrastructure/asset management.

These pillars represent the primary areas of focus for water utilities and authorities seeking to minimise and control real losses within their distribution networks. These *Four Pillars of Real Losses* provide a comprehensive framework for water utilities to systematically address and manage the real losses in their distribution systems. By focusing on pressure management, speed and quality of repairs, active leakage control, and infrastructure/asset management, utilities can work towards achieving more efficient and sustainable water distribution practices (Hamilton & Charalambous 2024).

The water losses projections have been obtained from *The Status of Non-Revenue Water in The Province of Kwazulu-Natal as of end of the 2022/23 Financial Year* (Umgeni Water 2023b). Figure 8 indicates the water losses for KwaZulu-Natal. It can be seen that the study area, particularly eThekwini, encounters excessive losses. With appropriate water management strategies, water service authorities can reduce these water losses, which will then ultimately result in reduction in carbon emissions.

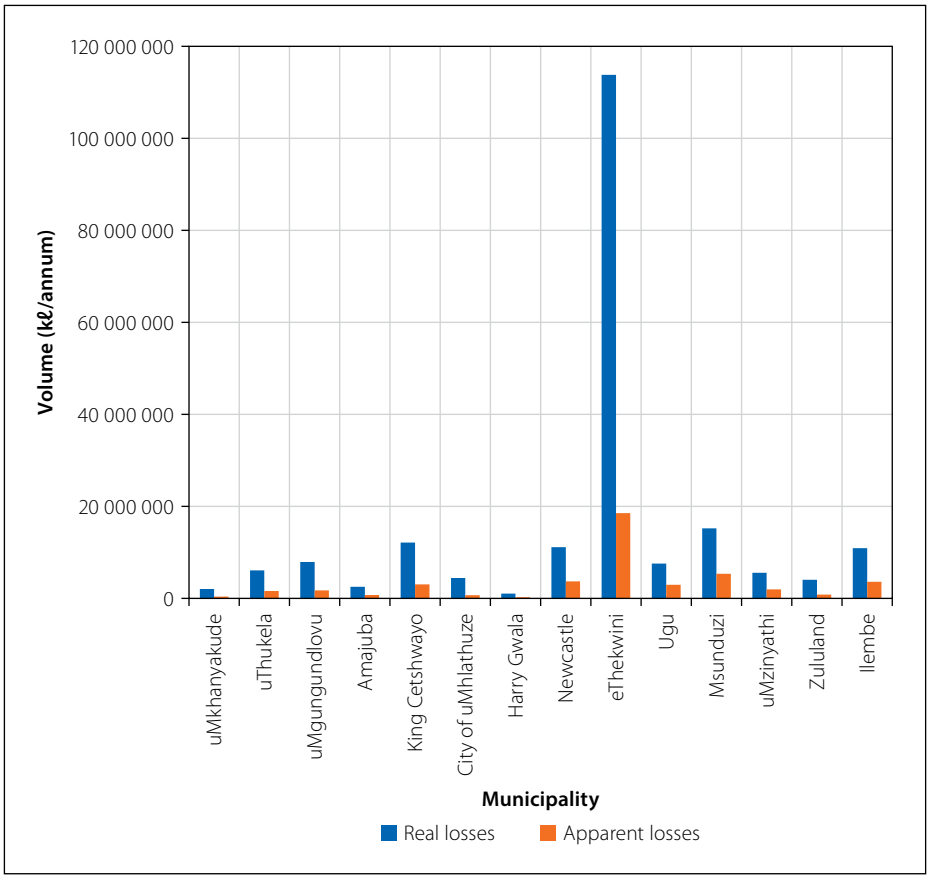


Figure 8 Water losses per municipality (Umgeni Water 2023b)

Total energy production

The production of potable water consumes a large amount of energy. As South Africa faces energy problems, which have been a major concern over the past decade, reducing the energy consumption in the water industry should be an important measure. GHG emissions are associated with electricity consumption in the water supply processes, and by reducing water leakage through measures to reduce non-revenue water, GHG emissions associated with the supply of excess water at the baseline will be reduced.

Carbon footprint can be described as the total amount of carbon dioxide, methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) (expressed as carbon dioxide equivalents or CO_2e) for which an organisation or site is responsible or has control over, and which result from business activities. As shown in Figure 9, data obtained from the CSIR Energy Centre Statistics of utility-scale power generation in South Africa in 2021 (Pierce & Ferreira 2022) indicates that South Africa's major source of electricity is coal, which accounts for approximately 73.2% of the total energy generation source. Nuclear generation accounts for 3.5%, gas and diesel generation 6.4%, wind generation 5.6%, and solar generation 4.1%. Hydro generation accounts for 1.1%, while CSP and pumped storage generation account for 0.9% and 5.1%, respectively.

South Africa, together with the International Renewable Energy Agency (IRENA), aims to pave the way to the promotion of accelerated renewable energy development through a series of activities that include the development of global, regional and country-level studies (IRENA 2020). This involves implementation of renewable energy to source the major part of the country's energy requirements, thus reducing the usage of coal. As shown in Figure 10, solar and wind generation are expected to play a considerably larger role in primary energy supply in South Africa by 2030, respectively increasing from 7 PJ and 18 PJ in 2015 to 216 PJ and 144 PJ by 2030.

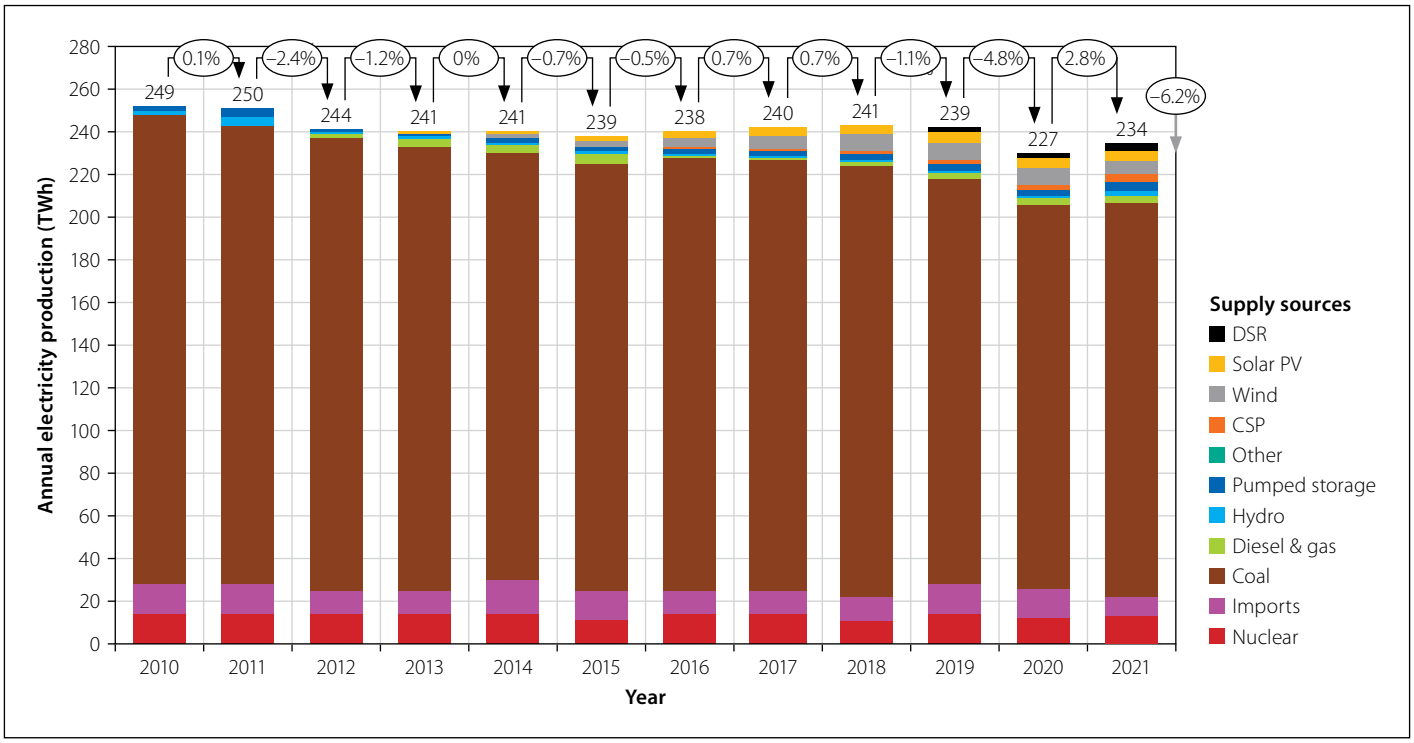
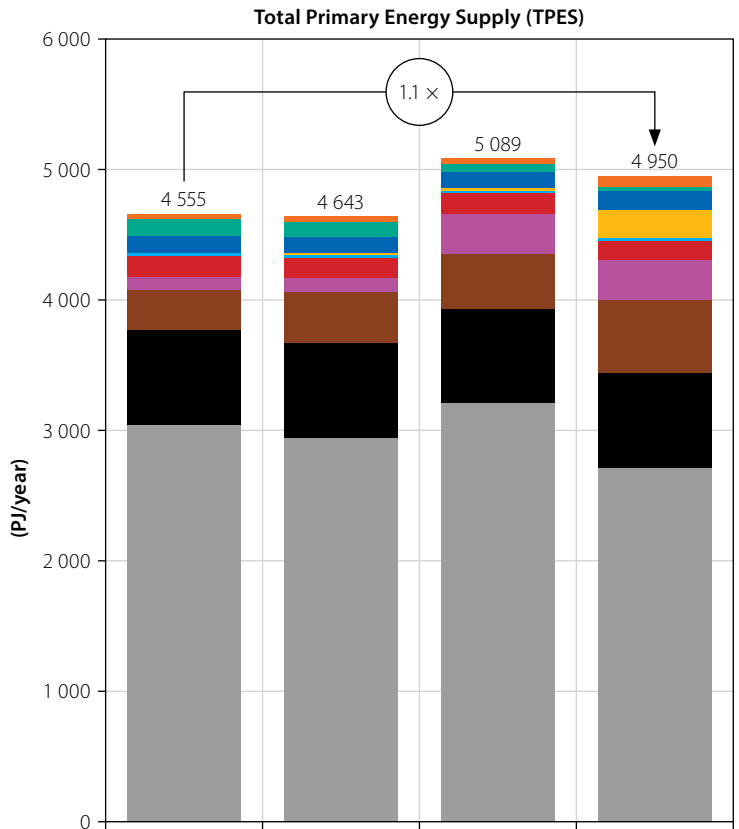


Figure 9 South African energy production sources (Pierce & Ferreira 2022)



	2015	2020	2025	2030
Electricity	44	44	44	92
Biomass	127	111	60	25
Wind	127	120	120	144
Solar	7	21	24	216
Hydro	18	19	19	19
Nuclear	161	157	161	148
Gas	99	100	306	306
Pretoleum products	308	399	418	560
Crude oil	727	727	727	727
Coal	3 048	2 946	3 212	2 714

Figure 10 Projected energy source (IRENA 2020)

Grid Emissions Factor (GEF)

The Grid Emissions Factor (GEF) is the total amount of GHGs emitted per unit of electricity generated for and distributed by an electricity grid.

According to a 2022 report by the South African Department of Forestry, Fisheries and the Environment, South Africa emitted approximately 379 $MtCO_2e$ during 2020 (DFFE 2022). In 2021 South Africa presented an updated mitigation target to represent a significant progression from the first Nationally Determined Contribution (NDC). South Africa committed to a fixed target for GHG emission levels of 398–510 $MtCO_2e$ by 2025, and 350–420 $MtCO_2e$ by 2030, compared to 398 and 614 $MtCO_2e$ between 2025 and 2030, as had been communicated in the first NDC. South Africa has also set the goal to reach net-zero emissions by 2050 in its Low-Emission Development Strategy (RSA 2021).

South Africa has one of the highest carbon intensities globally, which is due to its excessive coal usage for power generation. Various methodologies from different reporting regimes and countries were investigated as part of the development of South Africa's GEFs (Grid Emission Factors), which resulted in the development of the four GEFs listed below. (Table 4 shows the GEF for South Africa for each emission methodology.)

1. Domestic Generation Grid Emission Factor, which depicts the relationship between the amount of GHG emitted per unit of electricity that is generated within South Africa.
2. National Generation Grid Emission Factor, which depicts the relationship of emissions and end-user electricity consumption.
3. Transmission Losses Grid Emission Factor, which depicts the relationship between the emissions and end-user electricity consumption while considering transmission losses.
4. Distribution Losses Grid Emission Factor, which depicts the relationship between the emissions and end-user electricity consumption, while considering distribution losses.

The authors of this study focused on the National Generation Grid Emission Factor (NGGEF), as it is associated with electricity usage by the water authority end-user (DFFE 2024).

Studies by Brander *et al* (2011) indicated the Grid Emission Factor (GEF) for various countries globally. It can be seen from Figure 11 that South Africa is within the upper limits of the GEF values.

Table 4 Grid Emission Factor GEF (DFFE 2024)

	Grid Emission Factor (GEF) (tCO_2e/MWh)
Domestic Generation Grid Emission Factor (DGGEF)	1.013
National Generation Grid Emission Factor (NGGEF)	0.985
Transmission Losses Grid Emission Factor (TLGEF)	0.023
Distribution Losses Grid Emission Factor (DLGEF)	0.066

RESULTS

IWA International Standard Water Balance

The water balance is essential for managing water resources effectively, maintaining infrastructure, ensuring financial efficiency, complying with regulations, promoting sustainability, and providing reliable services to customers. By regularly

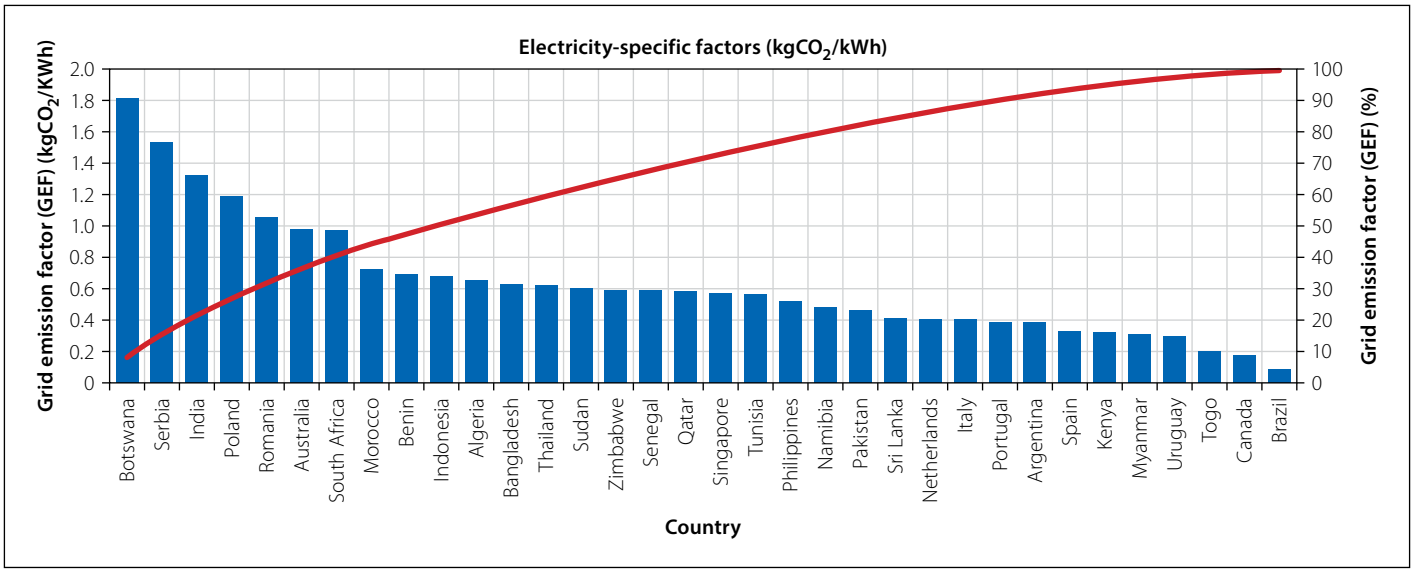


Figure 11 GEF values for countries globally (Brander *et al* 2011)

assessing and optimising the water balance, water utilities can contribute to the overall resilience and sustainability of their water supply systems (Hamilton & Charalambous 2024). The IWA Water Balance has been assessed and illustrated in Figure 12 for the Mgeni system for 2022/23.

A summary of the results for the water balance from 2016/17 to 2022/23 is shown in Figure 13. The results indicate that the water supplied to the system (SIV) increased from 396 million m^3/annum to 510 million m^3/annum (approximately an 8% annual increase). The water losses equate to approximately 133 million m^3/annum to 250 million m^3/annum (approximately 33–50% of the total SIV). From the water losses, real losses cover approximately 85–90% of the total water losses, while the remaining 10–15% losses are regarded as apparent losses. Further

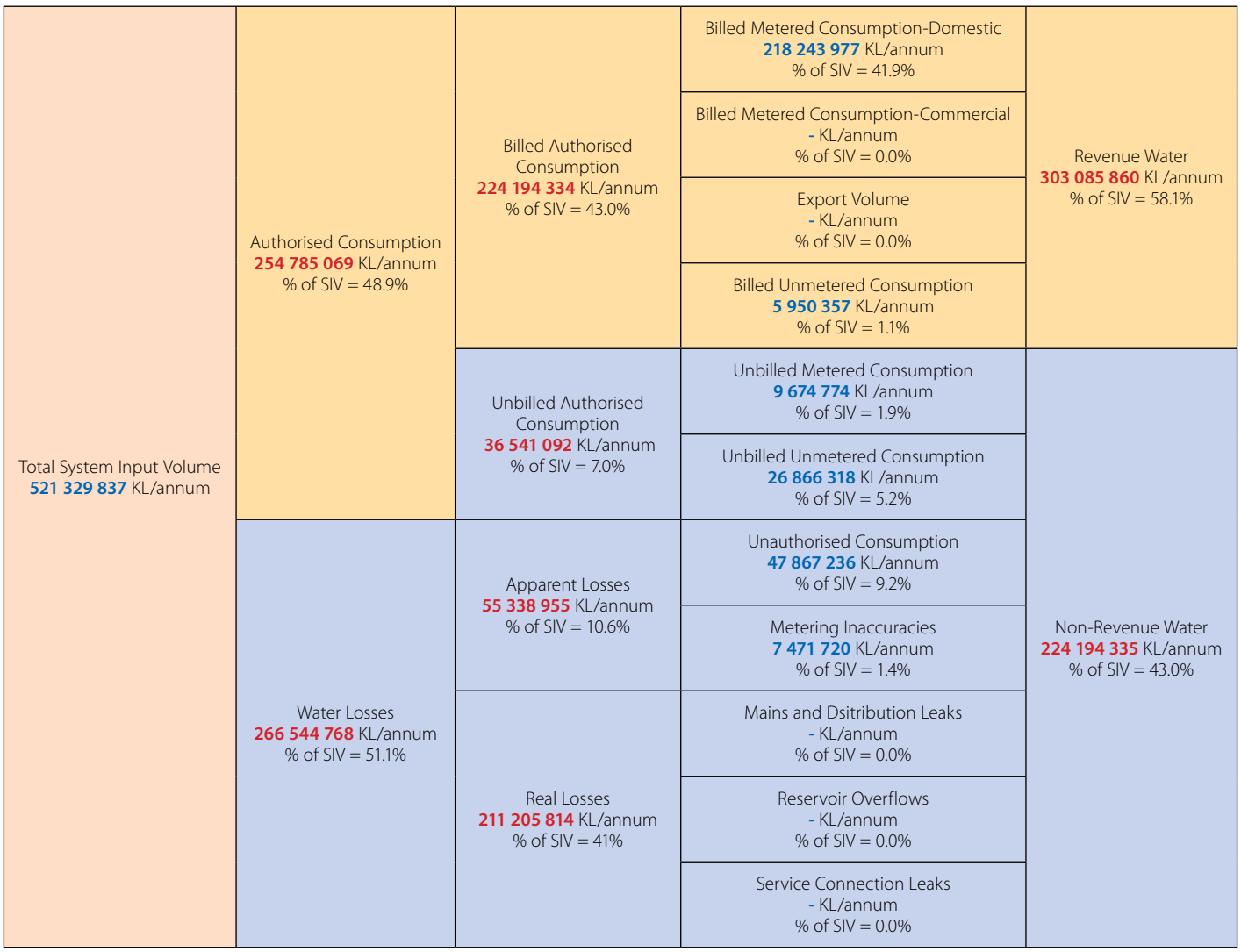


Figure 12 IWA water balance for Mgeni system 2022/23

analysis determined that the Unavoidable Annual Real Losses (UARL) equate to approximately 28 million m^3/annum to 35 million m^3/annum, with the avoidable losses being 85 million m^3/annum to 175 million m^3/annum.

It can be seen by these excessive water losses that there is a possibility to reduce the carbon emissions by implementation of the *Four Pillars of Real Losses* mentioned earlier in this paper, namely pressure management, leak detection and repair, active leakage control, and infrastructure/asset management. It can also be seen that the water losses increased from 2016/17 to 2022/23 by approximately 20%. This shows the dire need to implement WC/DM strategies to reduce these losses.

Energy consumption for water resources

As was mentioned earlier in this study, South Africa's main source of energy supply generation is coal which produces high levels of GHG. The Mgeni system produces about 509 million m^3 of potable water per year and depends on coal energy generation to source, treat and supply water to consumers. To get water to its consumers the Mgeni system uses approximately 180 000 to 200 000 MWh. This equates to approximately 0.8 to 1.1 KWh per KL of water produced. Based on the data for Umgeni-Thukela Water, the direct energy consumption and energy intensity per water supply across the Upper and Lower Mgeni system are presented in Figure 14 (Umgeni Water 2023a). Figure 15 indicates the energy utilised for the study area in the production of potable water for the end-user.

Carbon emission and grid emission factors

Carbon reduction initiatives are programmes or projects designed to mitigate or reduce the greenhouse gas emissions associated with human activities. The primary focus is on reducing the net carbon footprint to combat climate change and promote sustainability. These initiatives aim to balance the emission of greenhouse gases with activities that either capture, reduce or sequester an equivalent amount of carbon dioxide (CO_2) or other greenhouse gases (Hamilton & Charalambous 2024). Table 5 shows the relative carbon intensities for the study area.

The direct CO_2 emissions for the period 1970 to 2022 are presented in Figure 16 (Crippa *et al* 2023). The trends in CO_2

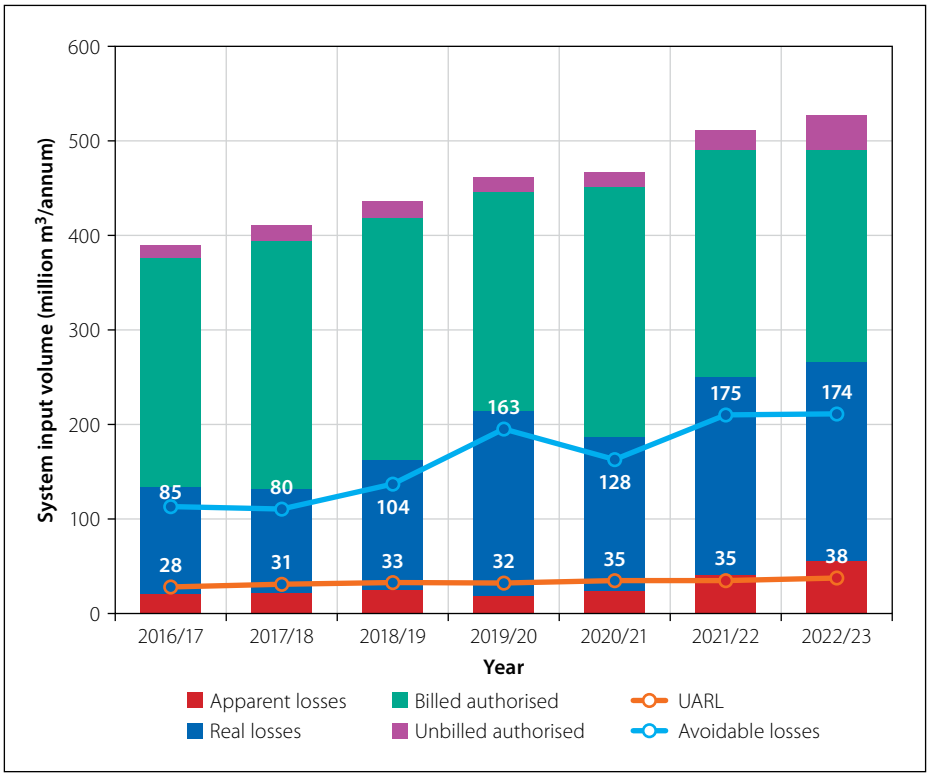
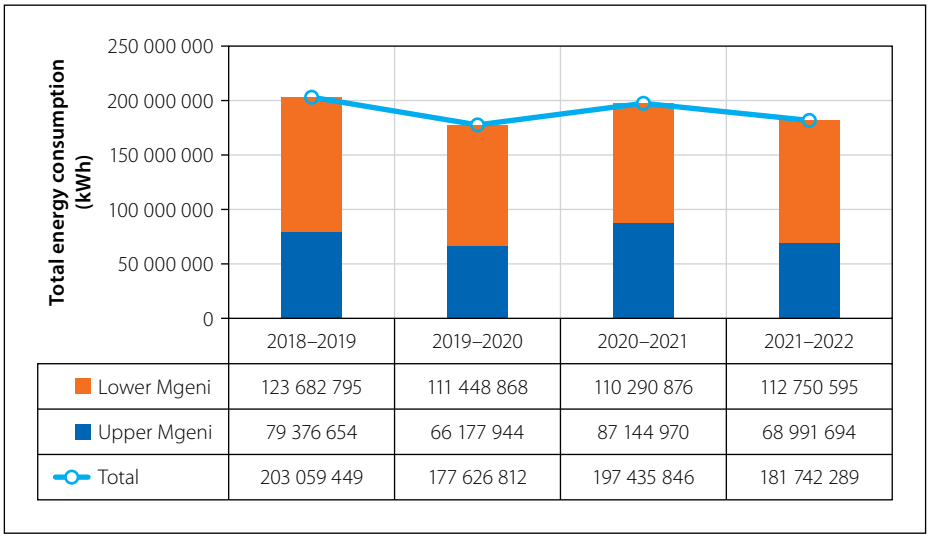
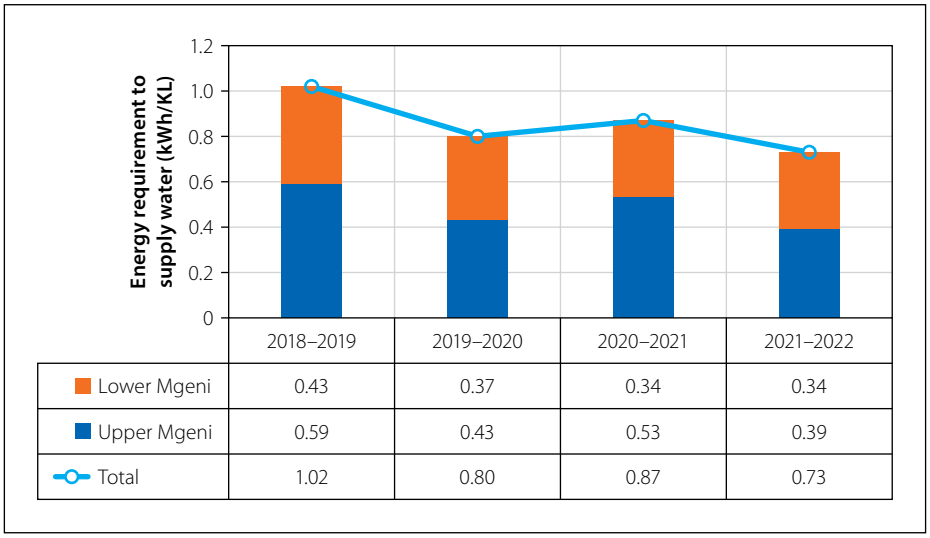


Figure 13 IWA water balance summary (Umgeni Water 2023b)



	2018–2019	2019–2020	2020–2021	2021–2022
Lower Mgeni	123 682 795	111 448 868	110 290 876	112 750 595
Upper Mgeni	79 376 654	66 177 944	87 144 970	68 991 694
Total	203 059 449	177 626 812	197 435 846	181 742 289

Figure 14 Total energy consumption for the Mgeni system (Umgeni Water 2023a)



	2018–2019	2019–2020	2020–2021	2021–2022
Lower Mgeni	0.43	0.37	0.34	0.34
Upper Mgeni	0.59	0.43	0.53	0.39
Total	1.02	0.80	0.87	0.73

Figure 15 Total energy consumption per KL supplied (Umgeni Water 2023b)

Table 5 Carbon intensity for the study area

	Grid emission factors (tCO_2e/MWh)					
	2007/08	2008/09	2009/10	2010/11	2011/12	2021/22
Carbon intensity	0.929*	0.980*	0.979*	0.990***	0.990***	0.985**

* Table 3: Marginal emissions factors for South African grid (tCO_2/MWh) (Spalding-Fecher, R 2011)
** Table 6: South Africa's 2021 Grid Emission Factor (DFFE 2024)
*** Table p 6: Grid Emission Factors (EXXARO 2013)

emissions variation across the country show similarities to energy consumption patterns. It can be seen that the CO_2 emissions increased from 1995 to 2009 when it reached a peak of approximately 550 million tCO_2/year. This was caused by high levels of coal power generation which accounted for approximately 75–86% of the total energy generation. The carbon emissions began to decline from 2010 as South Africa implemented carbon reduction strategies and policies. During the Paris Agreement South Africa committed that it would aim to reduce CO_2 emissions by 30% by 2025.

Mgeni system carbon emissions and carbon leakage reduction

In the analysis of the carbon emissions generated for the Mgeni system this study considered projected water demands with the current population growth of 1.1% per annum. The Mgeni system illustrates that the carbon emissions generated from the water demand increases exponentially due to the increase in water demand and continued use of coal energy generation. In developed countries, water losses are typically around 11%, while in a developing country such as South Africa the water losses are about 20–45% (Umgeni Water 2023b). The loss of water also wastes the electricity used for pumping and treatment.

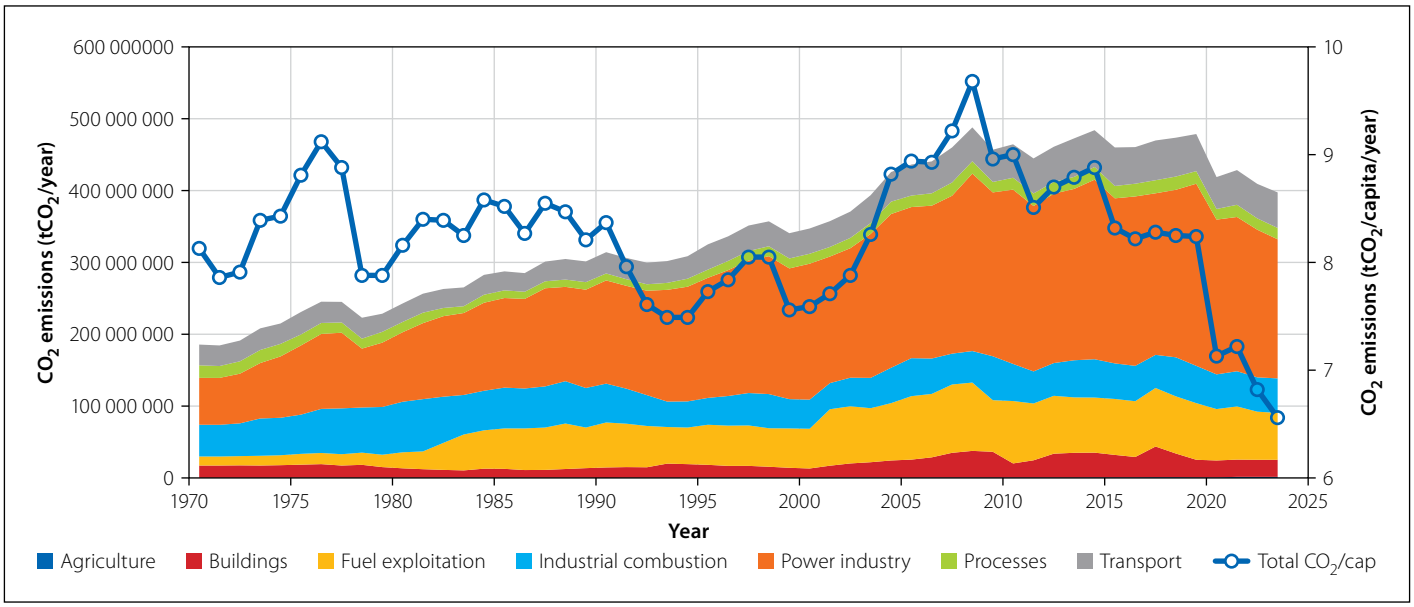


Figure 16 Carbon emissions per sector in South Africa (Crippa *et al* 2023)

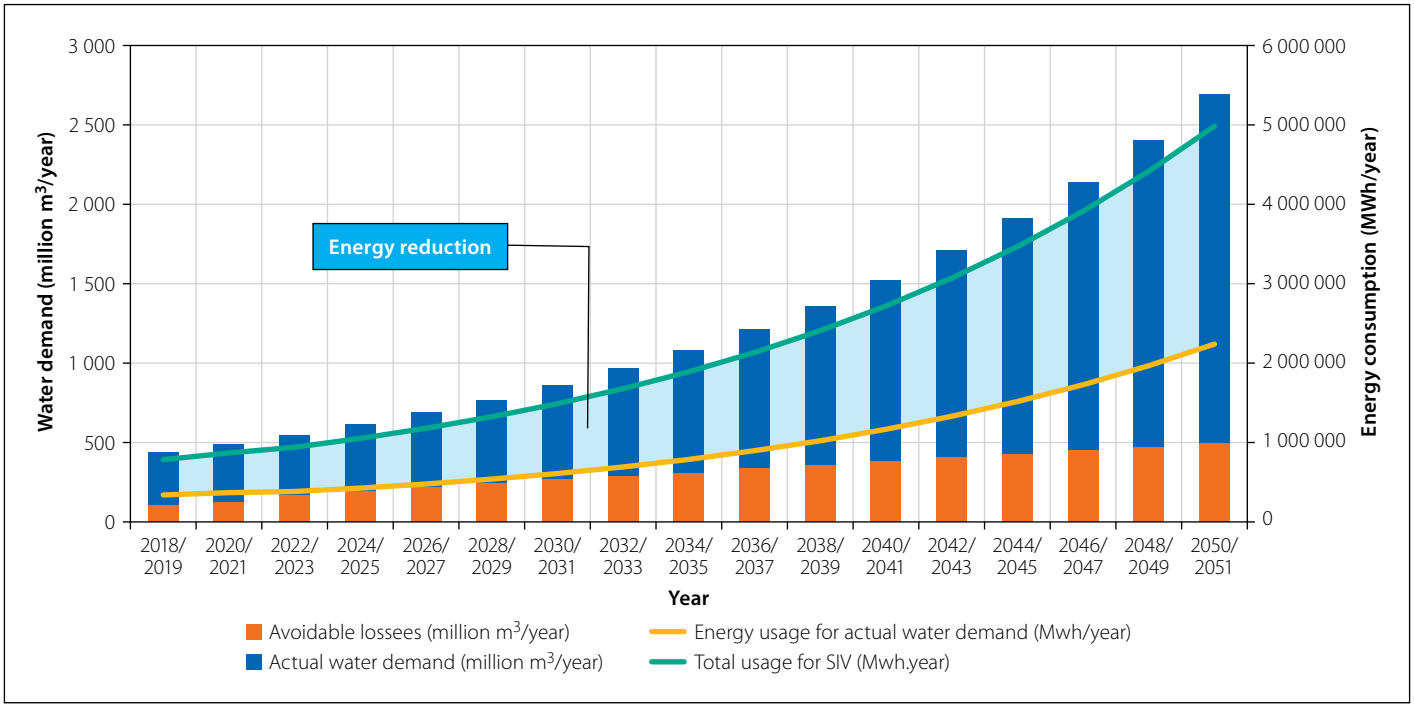


Figure 17 Water demand and energy usage

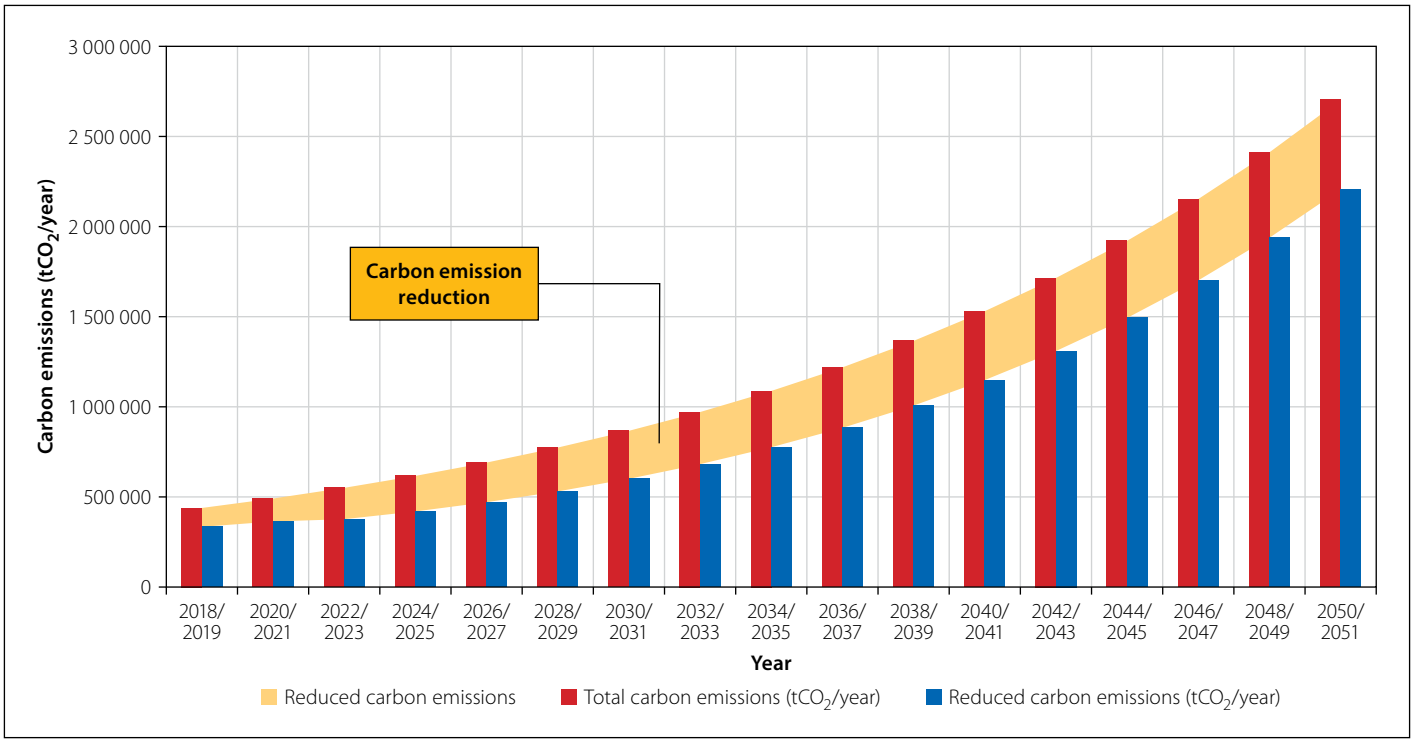


Figure 18 Carbon emission reduction considering current energy generation

Reducing water losses therefore presents a way to reduce electricity consumption, thereby lowering CO_2 emissions from the power grid (Thomas *et al* 2024).

Figure 17 illustrates the water demand for the period 2018/19 to 2050/51. It can be seen that the water demand increases from 436 million m³/year in 2018 to 2 690 million m³/year in 2050. It has also been estimated that the avoidable water losses are approximately 104 million m³/year to 495 million m³/year (Figure 11). Considering these avoidable losses, the total water supplied to the system (SIV) can be decreased should these avoidable losses be removed from the system. Figure 17 also indicates the energy reduction that can be achieved by removing or reducing the water losses from the system.

By removing the avoidable losses from the system, the water demand decreases to 332 million m³/year in 2018 and 2 195 million m³/year in 2050. This results in a decrease in energy usage of 339 124 MWh/year in 2018 to 2 239 324 MWh/year in 2050.

As described earlier in this paper, carbon emission is a byproduct of energy usage such as the burning of coal, and South Africa's major energy generation is from coal power. If South Africa continues to use coal as its main source of energy generation, carbon emissions will tend to increase, resulting in economic, environmental and social impacts. The carbon emissions produced by the current energy generation source, being mainly coal, is estimated to increase from 438 526 tCO_2/year in 2018 to approximately 2 703 060 tCO_2/year in 2050 (approximate increase of 58 490 tCO_2 per year). With a leakage reduction from water losses the carbon emissions could be reduced by 104 489 tCO_2/year in 2018 to 497 327 tCO_2/year in 2050 (nearly 18–25% reduction on carbon emissions), as illustrated in Figure 18.

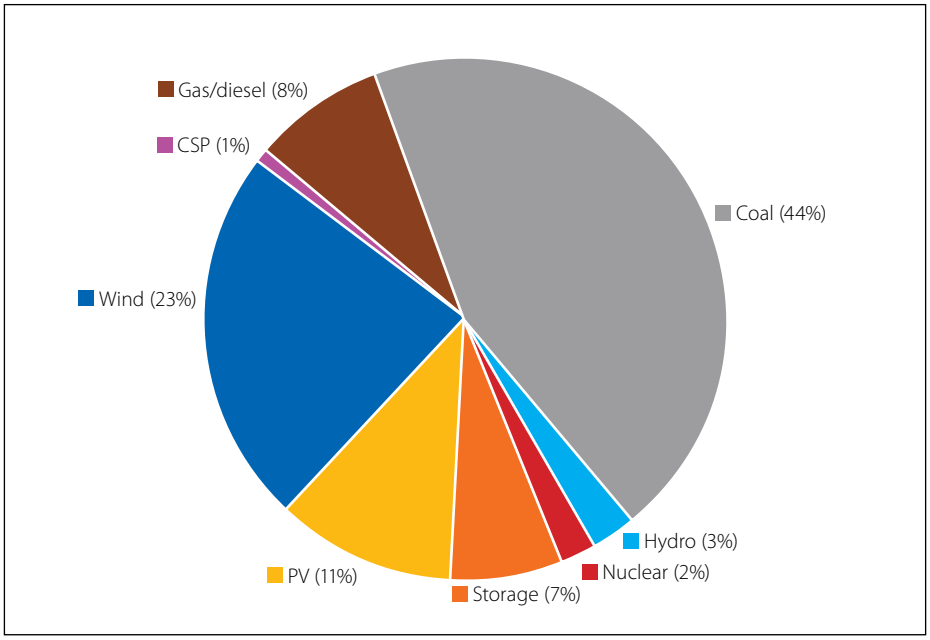


Figure 19 Energy source generation by 2030 (UNCC 2020)

As South Africa aims to reduce coal power generation by 2030, this will play a significant role in achieving net-zero. South Africa's Low Emissions Development Strategy 2025 (UNCC 2020) allows for renewables to be added to the electricity supply mix to meet growing demand and to replace coal power stations that will be decommissioned. The estimated energy generation is shown in Figure 19, with coal generation reducing from 73.2% in 2021 to 44.0% in 2030.

The implementation of renewable energy will drastically reduce the carbon emissions. Table 6 shows the GEF for the respective renewable energy sources.

An analysis of carbon emissions, considering the implementation of WC/DM and renewable energy, was conducted and is shown in Figure 20. It can be seen that in 2030, when the renewable energy

Table 6 GEF for renewable energy sources (Matsuda-Dunn *et al* 2024)

	Grid Emission Factor (GEF) (tCO_2e/MWh)
Hydropower	0.021
Nuclear	0.013
Storage	0.007
Photovoltaic (PV)	0.043
Wind	0.013
Concentrated Solar Power (CSP)	0.028
Gas / Diesel	0.486

is planned to be fully implemented, there is a drastic drop in emissions. The carbon emissions produced with the renewable energy generation are approximately 333 781 tCO_2/year in 2018 and increase to 1 191 831 tCO_2/year in 2050 (approximate increase of 26 814 tCO_2/year).

IWA Standard Carbon Balance (Leakage Emissions Initiative)

The study conducted an assessment of the IWA Standard Carbon Balance to identify the amount of carbon produced during the production of water for 2022/23. As illustrated in Figure 21, the total water supply (SIV) contributes to 373 293 tCO_2/year of carbon emissions. The water losses are approximately 266 million m^3/year, producing 190 857 tCO_2/year of carbon emissions.

It can be seen by the excessive water losses that it is possible to reduce the carbon emissions by implementing the *Four Pillars of Real Losses*. It can also be seen that the water losses increased from 2018/19 to 2022/23 by 25%. This shows the dire need to implement WC/DM strategies to reduce these losses, which will in turn result in carbon emission reduction.

DISCUSSION AND CONCLUSION

In this paper, the assessment of carbon emissions from water supply have been studied using a water balance approach considering the water losses occurring in the system. As water demand continues to increase exponentially, so do water losses within the systems. The result from this study provides accounting on the quantity of carbon produced to supply water to the system and provides an understanding of how water losses effect carbon emissions. The findings of this study indicate that the supply of potable water contributes substantially to carbon emissions, primarily through energy-intensive processes.

The analysis determined that the total water supply (SIV) produced approximately 438 526 tCO_2/year in 2018/19 and will produce 2 703 060 tCO2/year in 2050/51 with the current major energy generation source being coal. By reducing water losses, carbon emissions can be reduced to approximately 334 037 tCO_2/year for 2018 and 2 205 734 tCO_2/year in 2050, thereby resulting in an 18–25% decrease in carbon emissions.

Further analysis of the carbon emissions, considering renewable energy, determined that, with implementation of renewable energy and WC/DM, the carbon emissions could be approximately 333 781 tCO_2/y in 2018/19 and 1 191 831 tCO_2/year in 2050/51.

In order to move towards a more sustainable water supply system, it is crucial to implement effective mitigation strategies that can help with reducing carbon emissions. Implementing energy-efficient practices, such as utilising cutting-edge technologies and optimising operations, presents a viable solution for curbing energy usage and ultimately reducing carbon emissions. Incorporating sustainable energy sources, like solar and wind power, into water supply systems can greatly reduce carbon emissions, as well as improve resilience against energy price fluctuations and supply disruptions. Implementing the *Four Pillars of Real Losses* provides action to mitigate high water losses, as can be seen from the implementation of pressure management by the City of Cape Town that had successfully installed pressure-reducing valves across several districts to maintain consistent water pressure, and saw pressure reduction of 30%, leading to a significant reduction in leaks, bursts, and overall consumption, thereby saving approximately 13.4 million m^3/year of potable water (Meyer *et al* 2009). Active leakage control

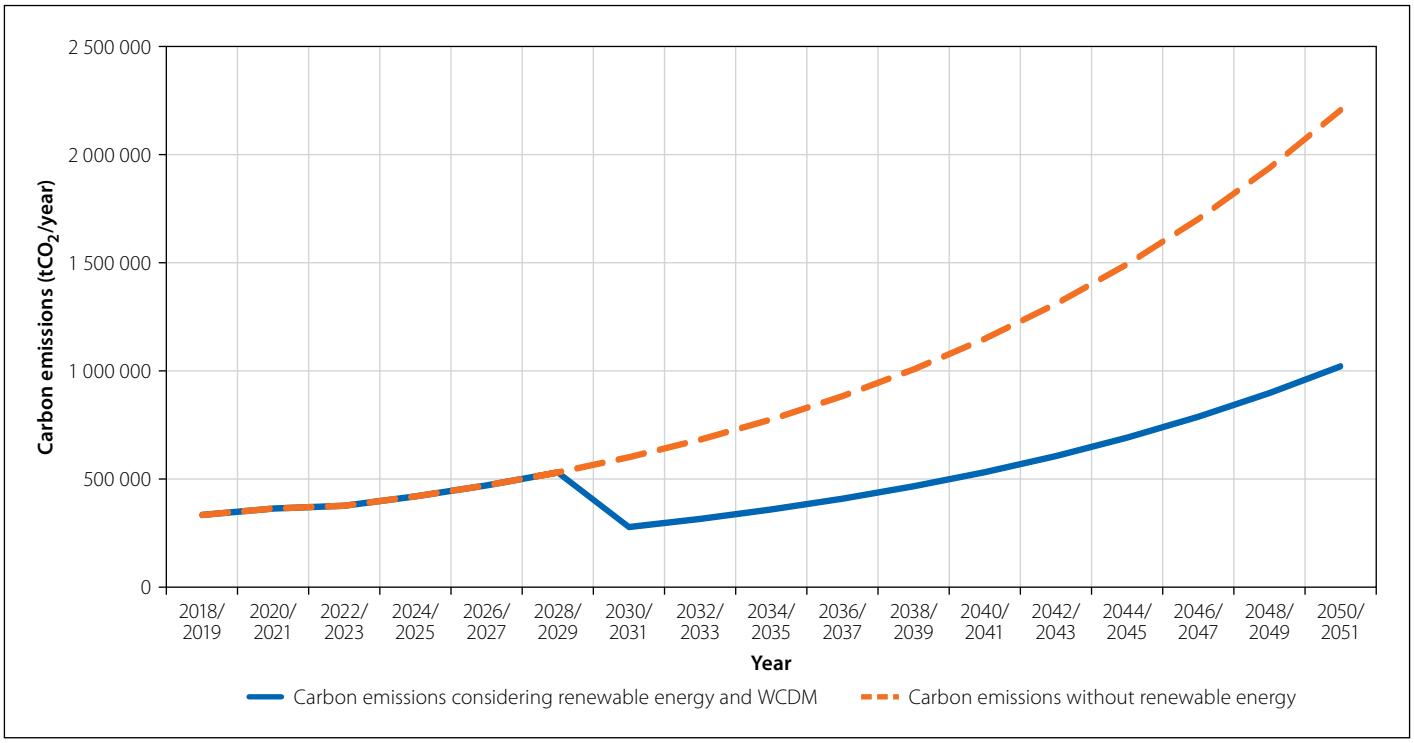


Figure 20 Carbon emission reduction considering WC/DM and renewable energy generation

<table>
<tr><td rowspan="10">Total System Input Volume
373 293 tCO_2/year</td><td rowspan="5">Authorised Consumption
182 436 tCO_2/year
% of SIV = 48.9%</td><td rowspan="3">Billed Authorised Consumption
160 532 tCO_2/year
% of SIV = 43.0%</td><td>Billed Metered Consumption-Domestic
156 271 tCO_2/year
% of SIV = 41.9%</td><td rowspan="3">Revenue Water
217 022 tCO_2/year
% of SIV = 58.1%</td></tr>
<tr><td>Billed Metered Consumption-Commercial
- tCO_2/year
% of SIV = 0.0%</td></tr>
<tr><td>Export Volume
- KL/annum
% of SIV = 0.0%</td></tr>
<tr><td>Billed Unmetered Consumption
4 261 KL/annum
% of SIV = 1.1%</td></tr>
<tr><td rowspan="2">Unbilled Authorised Consumption
26 165 tCO_2/year
% of SIV = 7.0%</td><td>Unbilled Metered Consumption
6 928 tCO2/year
% of SIV = 1.9%</td><td rowspan="7">Non-Revenue Water
160 532 tCO_2/year
% of SIV = 43.0%</td></tr>
<tr><td>Unbilled Unmetered Consumption
19 237 tCO_2/year
% of SIV = 5.2%</td></tr>
<tr><td rowspan="5">Water Losses
190 857 tCO_2/year
% of SIV = 51.1%</td><td rowspan="2">Apparent Losses
39 625 tCO_2/year
% of SIV = 10.6%</td><td>Unauthorised Consumption
34 275 tCO_2/year
% of SIV = 9.2%</td></tr>
<tr><td>Metering Inaccuracies
5 350 tCO_2/year
% of SIV = 1.4%</td></tr>
<tr><td rowspan="3">Real Losses
151 232 tCO_2/year
% of SIV = 41%</td><td>Mains and Dsitribution Leaks
- tCO_2/year
% of SIV = 0.0%</td></tr>
<tr><td>Reservoir Overflows
- tCO_2/year
% of SIV = 0.0%</td></tr>
<tr><td>Service Connection Leaks
- tCO_2/year
% of SIV = 0.0%</td></tr>
</table>

Figure 21 Mgeni system carbon balance – 2022/23

(ALC) strategies aim at the prompt detection and repair of burst pipes which could possibly reduce water losses by 15%, resulting in a reduction in energy consumption and ultimately carbon emission reductions. The implementation of policy and legislative measures is crucial in facilitating the shift towards water supply systems that have a low carbon footprint. The South African government has set ambitious targets to reduce emissions in line with the Paris Agreement. To encourage the adoption of sustainable practices, they have also implemented regulatory frameworks and financial incentives.

To effectively reduce carbon emissions from water supply systems, it is essential to adopt a comprehensive strategy that involves a combination of technological advancements, supportive policies, and collaborative efforts among institutions. Stakeholders can make a significant contribution towards achieving global climate goals and securing clean and dependable water resources for present and future generations by giving priority to sustainability principles and adopting a paradigm shift towards low-carbon water infrastructure. The focus should be on implementing pressure management by identifying critical zones in the distribution system and installing pressure-reducing valves to regulate pressure, and also by shifting to smart meters, regular active leak detection and control, more efficient repairing of leakages, enhanced ways of reporting leaks, and lastly developing an approach to replace ageing and deteriorating pipes within the system.

Calculating carbon emissions by using the water balance approach presents several limitations in research. One key challenge is the complexity of accurately modelling the water balance. The water balance has been modelled using the data obtained from various reports, as referenced. Data availability and precision also pose significant barriers, as inconsistencies or gaps in water and energy-use records can lead to inaccurate estimations. In order to achieve the Sustainable Development Goals (SDGs), high water losses and excessive energy usage are significant challenges, particularly those related to SGD 6 (clean water and sanitation), SDG 7 (affordable and clean energy), and SDG 13 (climate action). Water losses and wastage hinder efforts to provide universal access to clean water and sanitation. Additionally, increased energy consumption, particularly from non-renewable sources, increases carbon emissions which in turn results in rapid movement towards climate change.

Finally, implementing water conservation and demand management offers significant economic, environmental and social benefits. This reduces the need for extensive water treatment, infrastructure expansion, and energy consumption associated with water extraction and distribution, resulting in economic benefits. In terms of the environment, these strategies protect ecosystems by reducing water waste, reducing pressure on freshwater sources, and mitigating the effects of drought and climate change. As a social benefit, water conservation ensures reliable access to clean water for communities, especially

in areas with limited water resources. It fosters a culture of sustainability and responsible resource use, improving quality of life for future generations.

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