



Article GHG Emission Reduction Opportunities for Road Projects in the Emirate of Abu Dhabi: A Scenario Approach

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Abstract: The transportation sector is considered one of the driving forces behind the increased release of greenhouse gases (GHGs), with road transport being this sector's main emissions contributor. In turn, efforts should be devoted to reducing emitted GHGs from this sector, and many such opportunities lie in the road transport life cycle. This paper investigated fourteen emission reduction scenarios based on the green initiatives issued by the Abu Dhabi Government. The explored measures are either related to road works and road municipal services or to traffic movement. The proposed measures were evaluated with reference to a baseline study previously reported by the authors for three different road projects in Abu Dhabi city. Findings reveal that normalized GHG emission reduction could be significantly reduced by (i) replacing 30% of internal combustion engine passenger cars with battery electric vehicles where the power demand is covered almost equally from nuclear and liquified natural gas (LNG) sources, (ii) reducing the number of passenger cars by 10%, and (iii) having one-fifth of passenger cars powered by LNG. A lesser significant reduction could be achieved by replacing conventional lamps with light-emitting diode (LED) lamps or by having onefourth of lighting powered by solar energy. Even lesser reduction could be achieved by (i) replacing a portion of Portland cement with ground granulated blast furnace slag in concrete structures, (ii) fully utilizing treated sewage effluent for roadside-plant irrigation, (iii) reducing desalinated water used for roadside-plant irrigation by 20%, and (iv) increasing the number of higher efficiency passenger cars by 10%. Replacing hot-mix asphalt with warm-mix asphalt and using asphalt with a high stiffness modulus in the base layer results in low emission reduction. The use of 15% recycled asphalt or the use of 50% recycled aggregate in road construction has the least impact on emission reduction. When all explored scenarios were combined, an overall normalized GHG emissions reduction of 9-17% during the road project life cycle could be achieved.

Keywords: greenhouse gases; road project life cycle; RoadCO₂; emission reduction; comparative analysis

1. Introduction

There is strong evidence that anthropogenic greenhouse gas (GHG) emissions are the main drivers behind climate change [1]. According to the Intergovernmental Panel on Climate Change (IPCC), the average global surface temperature rose about 0.85 °C from 1880 to 2012. It is estimated that the 2010 GHG emissions levels must be cut by 40% to 70% by 2050 to prevent a greater than 2 °C increase in the global mean temperature—a threshold that may avoid the most severe climate change impacts [2]. Projection scenarios



Citation: Maraqa, M.A.; Albuquerque, F.D.B.; Alzard, M.H.; Chowdhury, R.; Kamareddine, L.A.; El Zarif, J. GHG Emission Reduction Opportunities for Road Projects in the Emirate of Abu Dhabi: A Scenario Approach. *Sustainability* **2021**, *13*, 7367. https://doi.org/ 10.3390/su13137367

Academic Editor: Aoife Ahern

Received: 27 May 2021 Accepted: 17 June 2021 Published: 1 July 2021

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). have shown that the Earth will warm by 2.6 to 4.8 $^{\circ}$ C by the end of the century if no further mitigation actions are taken to reduce GHG emissions [3]. Moreover, climate change would continue for hundreds of years due to the inertia in the global climate system even if the GHG emissions abruptly ceased [1].

Transportation is the fastest-growing major contributor to climate change. This sector accounts for nearly 14% of the global GHG emissions [4]. Currently, it is considered the second-largest energy consumer after the industrial sector [5]. GHG emissions from the transport sector are predicted to increase rapidly worldwide, with an expected increase of 80% by 2030 compared to the levels in 2007 [5]. Economic development and population growth have caused a substantial expansion of the road network over the past years. More than 25 million kilometers of new roads are expected to be built globally by 2050, a 60% increase as compared to the number of kilometers of roads built prior to 2011 [6].

Research on GHG emissions produced by road project construction, maintenance/rehabilitation, and operation has taken different directions. Some studies focused on establishing a framework for estimating emitted GHGs during road construction with the intent of utilizing this framework during the early stage of a project (i.e., planning and design stage) [7–9]. Such effort may likely aid road designers in incorporating sustainable concepts into their work.

Other studies were conducted to estimate GHGs produced by road projects utilizing current construction practices [7,10–16]. For example, Haung et al. [10] compared estimates of CO₂ emissions produced during the construction of three road cases—one in the United Kingdom, another in the United Arab Emirates (UAE), and a third one in India. They found variations in the normalized emissions among the studied cases and attributed that to differences in technical specifications and local requirements, material availability, construction techniques, and the extent to which concrete structures were used. Nonetheless, some studies [7,11–14] have shown that the bulk of the emissions associated with road construction and maintenance activities are often associated with the upstream emissions embodied in the materials used. Moreover, Barandica et al. [15] concluded that the operation of off-road machinery for earthwork accounted for 60% to 85% of the total construction emissions of four studied road cases in Spain.

Another group of studies focused on exploring potential alternatives to reduce GHG emissions during the entire road project life cycle. These alternatives assessed GHG emission reduction resulting from (i) reduced traffic volume [17], (ii) increased usage of more fuel-efficient vehicles [17,18], (iii) promoting car-sharing [19], (iv) increased usage of natural gas or electrically powered vehicles [18,20,21], (v) increased usage of public transport and non-motorized transport modes [22], (vi) increased usage of renewable energy sources for powering road lighting [23], (vii) adopting alternative project staging approach [24], (viii) increased adoption of in-place recycling during pavement construction and rehabilitation [25], (ix) replacing hot-mix asphalt with warm-mix asphalt [23,26,27], (x) partially replacing Portland cement (PC) with fly ash (FA) and ground granulated blast furnace slag (GGBFS) [28,29], and (xi) avoiding overdesign practices [28].

Another set of studies focused on assessing the efficacy of electric vehicles (EVs) in reducing carbon footprint [30,31]. EVs have drawn a lot of attention from researchers and governments as they have been seen as an important tool in the fight against climate change [32]. For example, battery EVs (BEVs), more specifically, rely solely on electricity stored in a battery to power an electric motor and, therefore, as long as much of the electricity consumed by BEVs comes from a clean source, BEVs have been found to be effective in producing a much smaller carbon footprint as compared to internal combustion engine vehicles (ICEVs). Otherwise, adoption of BEVs may actually be detrimental to air quality [33,34]. However, in the case of grids fed by different energy sources, assessing the efficacy of BEVs in reducing emissions has been a particularly complex task given that in such scenarios, much of the emissions produced by BEVs may be dependent on charging schemes [35]. Nonetheless, a significant amount of emissions produced by BEVs are actually emitted upstream (i.e., during battery manufacturing) [36]. Indeed, a number of

studies have compared the life-cycle emissions between BEVs and ICEVs. BEVs presented a lower life-cycle emission profile only after they reached certain mileage ranges and as long as replaced batteries were repurposed [30]. Thus, previous studies have shown that the effectiveness of BEVs in reducing emissions is highly dependent on factors such as the grid energy mix and assumptions made during the vehicle life cycle (i.e., upstream emissions and battery duration/repurpose).

Despite the progress made in establishing a solid foundational framework for assessing GHG emissions associated with road project construction/maintenance/rehabilitation as well as traffic operations, it is still difficult to generalize the findings of other studies or even compare emission estimates among different countries. This is mainly because construction material availability, construction/maintenance practices, and energy sources may significantly differ among different countries [37–41]. Aside from that, many of the tools used to estimate GHG emissions produced by road projects vary in their extent of coverage of the different project phases as well as the activities involved within each phase [16,42,43].

With the growing concern regarding climate change and sustainable development, the government of the United Arab Emirates (UAE) has launched various initiatives aimed at reducing carbon emissions across all sectors. While the country's total (i.e., in absolute terms) GHG emissions due to road transport are significantly less than those of other countries like China and the United States (US), emissions normalized by national road mileage are alarmingly high. For example, the normalized road-transport-related GHG emissions in the Emirate of Abu Dhabi, the largest emirate in the UAE, are nine times higher than those of China and 2.5 times higher than those of the US [43]. Recently, Alzard et al. [16] provided an estimate of the GHG emissions of three road projects in Abu Dhabi city and highlighted the activities that contribute most to their carbon footprint. The authors found that estimates of the normalized GHG emissions from road project construction are much higher than those from projects undertaken by their counterparts in the European Union.

Thus, there is a need to explore GHG emission-reduction options in order to make the UAE's road construction projects, as well as road transport operations, more environmentally sustainable. In this study, we utilized the findings of Alzard et al. [16] to develop insight into the potential impact of specific measures that could be implemented either in road works or during traffic operation to reduce GHG emissions. This analysis may provide decision-makers and designers insights into mitigation measures to reduce the carbon footprint of road construction projects and traffic operations in the UAE. Meanwhile, the general approach presented here may be of value in application to other regions.

2. Methodology

2.1. Baseline Cases

The baseline cases include three road projects in Abu Dhabi city, UAE (Figure 1). Two of the cases are primary roads, while the third is a secondary road. A typical cross-section of a primary road in Abu Dhabi consists of the following layers: a subgrade of 430 mm, an aggregate base of 500 mm, an asphalt base of 280 mm, and an asphalt wearing surface of 150 mm. For a secondary road, the layers are a subgrade of 300 mm, an aggregate base of 200 mm, an asphalt base of 60 mm, and an asphalt wearing surface of 50 mm. Table 1 lists some characteristics of the considered baseline cases. Details about these cases are provided by Alzard et al. [16], but a brief description is provided below.

Case 1 involves the construction of an urban, local secondary road network and utilities (such as the installation of new telecommunication and electricity) in the Al Rahba area along the Abu Dhabi-Dubai highway. These roads are two-lane roadways with a total width of 7.30 m. The roads have a 0.35 m wide outer shoulder and a 2.0 m wide sidewalk in each direction. The project also included the construction of major utility works features such as water, electrical, and telephone ducts, irrigation ducts, and stormwater and sewage drainage infrastructure.



Figure 1. Location of the three studied road cases in Abu Dhabi city (adopted from Alzard et al. [16] with modification).

| Parameter | Case 1 | Case 2 | Case 3 |
|--|-----------|------------|--------------|
| Road type | Secondary | Primary | Primary |
| Project construction duration (months) | 20 | 27 | 27 |
| Project construction initiation date | June 2014 | April 2007 | October 2009 |
| Length (km) | 30 | 3.6 | 2.87 |
| Posted speed limit (km/h) | 60 | 120 | 120 |
| Number of constructed lanes | 2 | 8 | 2 |
| Lane width (m) | 3.65 | 3.65 | 3.65 |

Cases 2 and 3 are primary roads. The former involves the upgrading of Al Salam Street, along with the construction of a 0.6-km tunnel and the widening of at-grade roads. The latter covers the widening of the existing Eastern Abu Dhabi Corniche road by adding a fourth traffic lane and a 3 m shoulder in each direction.

2.2. Estimation of GHG Emissions

GHG emissions of the baseline cases were estimated for the construction and operation phases by Alzard et al. [16] using the RoadCO₂ estimation tool. RoadCO₂ is a web-based tool developed to estimate GHG emissions during the entire life cycle of a road project [42].

The tool is equipped with a database that covers an extensive list of GHG-emitting, roadrelated activities, including those originating from both direct and indirect sources. Direct sources of emissions include emissions that originated within the boundaries of the project (for example, fuel use), whereas indirect emissions originated outside the boundaries of the project but are attributed to the project's carbon footprint (for example, emissions emitted from material processing). RoadCO₂ utilizes the methodology proposed by the Intergovernmental Panel on Climate Change (IPCC) for GHG emissions estimation [44]. The general equation used for estimating GHG emissions (E) for a particular activity is given by:

$$= AD \times EF$$
 (1)

where AD is the activity-related data and EF is the emission factor pertinent to that activity. Equations (2)–(4) were used to estimate GHG emissions during the construction phase due to material usage (E_{mat}), equipment usage (E_{eq}), and material and equipment transportation (E_{trans}), respectively.

Ε

$$E_{mat} = \sum (V_{mat} \times \rho) \times EF_{mat}$$
(2)

$$E_{eq} = \sum (FCR_{eq} \times N_{eq} \times t_{eq}) \times EF_{eq}$$
(3)

$$E_{trans} = \sum (M \times L_{trans}) \times EF_{trans}$$
(4)

where V_{mat} is the material volume (m³), ρ is the material density (kg/m³), EF_{mat} is the emission factor for material (kg CO₂e/kg), FCR_{eq} is the equipment fuel consumption rate (L fuel/h), N_{eq} is the number of equipment of a certain type, t_{eq} is the equipment operation duration (h), EF_{eq} is the emission factor for equipment (kg CO₂e/L fuel), M is the mass of transported material or equipment (kg), L_{trans} is the transportation distance (km), and EF_{trans} is the emission factor for transporting material (kg CO₂e/kg·km).

For the operation phase, emissions due to traffic movement by ICEVs (E_{ICEVs}), BEVs (E_{BEVs}), road lighting (E_{light}), and roadside-plant irrigation (E_{irrig}) were estimated using Equations (5)–(8), respectively.

$$E_{ICEVs} = \sum (FCR_{ICEV} \times N_{ICEV} \times L_{ICEV}) \times EF_{ICEV}$$
(5)

$$E_{BEVs} = \sum (E_{BEV} \times N_{BEV} \times L_{BEV} \times CF) \times EF_{BEV}$$
(6)

$$E_{light} = \sum \left(W_{lamp} \times N_{lamp} \times t_{lamp} \right) \times EF_{lamp}$$
(7)

$$E_{irrig} = \sum (IR \times N_{tree} \times t_{irrig}) \times EF_{irrig}$$
(8)

where FCR_{ICEV} is the ICEV fuel consumption rate (L fuel/km.ICEV), N_{ICEV} is the ICEV traffic volume (ICEV/y), L_{ICEV} is the ICEV travel distance (km), EF_{ICEV} is the emission factor for ICEV fuel consumption (kg CO₂e/L fuel)), E_{BEV} is the BEV electricity consumption efficiency (kwh/km.BEV), N_{BEV} is the number of BEVs (BEV/y), L_{BEV} is the BEV travel distance (km), CF is a factor to convert electricity consumed into energy (kBTU/kwh), EF_{BEV} is the emission factor for BEVs (kg CO₂e/kBTU). W_{lamp} is the lamp wattage (kW), N_{lamp} is the number of lamps, t_{lamp} is the lighting duration (h/y), EF_{lamp} is the emission factor for electricity consumption (kg CO₂e/kWh), IR is the irrigation rate (L water/d.tree), N_{tree} is the number of trees per type, t_{irrig} is the irrigation duration (d/y), and EF_{irrig} is the emission factor for water production (kg CO₂e/L water).

2.3. Baseline Activity Data and Emission Factors

Activity-related data used to estimate the emitted GHGs for the baseline cases were extracted from several internal documents obtained from the Abu Dhabi City Municipality (ADM) [16]. These documents included (i) a bill of quantities (BOQ) with drawings and design data, (ii) traffic counts, and (iii) the distribution of desalinated water and treated sewage effluent (TSE) for soft landscape irrigation. The BOQ documents provided information about the quantities of construction materials and the type of construction equipment used. Other ADM internal documents that were utilized to quantify the emitted

GHGs included the Technical Specifications and Design Manual, the Standard Drawings Manual, and the Public Realm Design Manual (see Table 1 of Alzard et al. [16]).

The three road cases were paved using hot-mix asphalt. Concrete mixes used in Cases 1 and 3 were composed of Portland cement (PC). The concrete mixes used for nonstructural purposes in Case 2 were composed of 65% PC and 35% FA, and those used for structural purposes were composed of 30% PC and 70% GGBFS. Details about the type and quantity of material used in the road construction of the three cases as well as the type and number of construction equipment used were provided by Alzard et al. [16].

In this study, the reduction of emissions for road projects was explored through the use of innovative materials and technologies with a focus on road works, road lighting, roadside-plant irrigation, and traffic movement. Data related to such activities were extracted from Alzard et al. [16] as listed in Table 2. Construction materials and equipment were transported from the Mussafah Industrial Area (about 24-48 km from the location of the case studies), whereas the aggregates were transported from the Emirate of Fujairah (~250–300 km from the location of the studied cases).

Table 2. Activity data related to materials used in road works, road lighting, roadside-plant irrigation, and traffic movement of the baseline cases (extracted from Alzard et al. [16]).

| Activity | Item | Unit | Case 1 | Case 2 | Case 3 |
|-----------------------|-----------------------------------|----------------|-----------|------------|------------|
| | Concrete: K140 | m ³ | 2502 | 0 | 2421 |
| | Concrete: K250 | m ³ | 1399 | 0 | 36 |
| | Concrete: K455 | m ³ | 5342 | 0 | 0 |
| | Concrete: K550 | m ³ | 0 | 0 | 33 |
| | Concrete: K140 (65% PC+35% FA) | m ³ | 0 | 15,301 | 0 |
| Material for road | Concrete: K250 (65% PC+ 35% FA) | m ³ | 0 | 2630 | 0 |
| works | Concrete: K415 (30% PC+70% GGBFS) | m ³ | 0 | 149,126 | 0 |
| | Concrete: K455 (30% PC+70% GGBFS) | m ³ | 0 | 212 | 0 |
| | Concrete: K550 (30% PC+70% GGBFS) | m ³ | 0 | 92 | 0 |
| | Aggregates | m ³ | 153,490 | 293,710 | 49,280 |
| | Asphalt | m ³ | 2858 | 2440 | 180 |
| | Steel | ton | 182 | 14,850 | 5 |
| | Passenger cars | veh/y | 3,193,090 | 27,550,010 | 7,593,069 |
| Traffic movement | Light trucks | veh/y | 6,714,804 | 37,669,054 | 10,381,982 |
| | Heavy trucks | veh/y | 1,994,821 | 7,833,222 | 2,158,917 |
| | Lamps (150 W) | lamp | 0 | 60 | 0 |
| Road lighting | Lamps (400 W) | lamp | 1271 | 1090 | 8 |
| 0 0 | Lamps (1000 W) | lamp | 0 | 428 | 50 |
| Pood plant irrigation | Palm trees | tree | 0 | 400 | 80 |
| Road-plant irrigation | Other trees | tree | 1538 | 200 | 23 |

Traffic counts provided by ADM classify vehicles as passenger cars, light trucks, and heavy trucks. All passenger cars and 60% of light trucks use gasoline, while the remaining 40% of light trucks and all heavy trucks use diesel. The water consumed for roadside-plant irrigation in Abu Dhabi city is made up of 75% TSE and 25% desalinated water. Road lighting in the three cases is currently provided using conventional (metal-halide and high-pressure sodium (HPS) lantern) lamps.

The values of the EFs used to estimate GHG emissions for the baseline cases were mostly adopted from the IPCC [44]. For a material that consists of a mixture of different materials, the EF was estimated as the weighted average of the EFs of the individual components of the mixture. EFs for concrete made with 65% PC and 35% FA or that made with 30% PC and 70% GGBFS were determined based on the findings of Tait and Cheung [29]. Values of the EF used in the baseline cases were provided by Alzard et al. [16] for the material consumed during the construction and the operation phases.

2.4. Baseline Emissions

GHG emissions during the construction and operation phases of the three baseline cases were obtained from Alzard et al. [16]. GHG emissions produced during road construction are due to activities related to the use of material and construction equipment as well as the transportation of these items to the construction site. Road construction involves several activities including road works, sewerage works, lighting and electrical works, landscaping, and street furnishing, as well as establishing other infrastructure utilities such as the irrigation network, stormwater network, telecommunication network, and water network. Activities that contribute to road GHG emissions during the operation phase include vehicle movement, street lighting, roadside-plant irrigation, and stormwater pumping. Table 3 lists emitted GHGs from road works, road lighting, roadside-plant irrigation, and traffic movement of the three road cases as determined by Alzard et al. [16]. Emissions from other activities reported by Alzard et al. [16] were not included, as they are not related to the explored scenarios in this study. The data in Table 3 will be utilized later as the basis for comparison with the emissions produced under the explored emission reduction scenarios.

Table 3. Emissions during the construction and operation phases of the three road cases (from Alzard et al. [16]).

| Category | Phase | GHG Emission Unit | Case 1 | Case 2 | Case 3 |
|---------------------------|--------------|--------------------------|--------|---------|--------|
| Road works | Construction | ton CO ₂ e | 15,372 | 61,236 | 8910 |
| Road lighting | Operation | ton CO_2e/y | 2045 | 5318 | 213 |
| Roadside-plant irrigation | Operation | ton CO_2e/y | 152 | 59 | 10 |
| Traffic movement | Operation | ton CO_2e/y | 13,345 | 102,610 | 22,505 |

2.5. GHG Emission Reduction Scenarios

2.5.1. Possible Options

Mitigation measures to reduce the GHG emissions produced by road projects can be related to activities carried out during all phases of a road project life cycle, starting as early as the design stage. Thus, emissions can be reduced by either reducing the quantity associated with an activity, substituting an activity with another one that has a lower emission factor, or by altering both measures at the same time.

Several mitigation scenarios can be explored with the intent of reducing GHG emissions associated with road construction practices. These include increasing the use of recycled materials or increasing the use of regionally available materials. An increase in the use of recycled materials can be achieved by utilizing recycled construction waste in road projects or by using reclaimed asphalt. Similarly, increasing the use of regionally available materials is expected to reduce emission due to material transportation.

Emissions can also be reduced during the construction phase by using GGBFS in the concrete mix to reduce cement content, replacing hot-mix asphalt with warm-mix techniques, or reducing emissions associated with construction equipment [14,26]. The use of thinner pavement layers with improved materials such as asphalt with a high stiffness modulus in the base layer is also an option [23]. This, in fact, will have a double positive effect, as it reduces the compaction effort, and thus the compaction time, while also reducing the quantity of material used. A third aspect of innovation is to optimize the use of available resources through construction management measures such as rational equipment and material usage, as well as optimal transport of construction vehicles and placement of road safety barriers.

During the traffic operation phase, several options to reduce GHG emissions can be explored. One scenario is to reduce traffic volume. This can be achieved by different means such as (i) increasing the market share of other transportation modes such as public and non-motorized transport, (ii) managing travel demand by adopting transport demand management strategies such as congestion pricing or taxing car owners, or (iii) promoting mixed land use development [45–48]. Another possible scenario is to alter traffic char-

acteristics by increasing the proportion of (i) higher-efficiency vehicles (in terms of fuel consumption), (ii) vehicles powered by liquefied natural gas (LNG), and (iii) electrically powered vehicles. Such options can be promoted through incentive/subsidy programs and/or taxation on low-efficiency vehicles. Previous work has indicated that improving vehicle energy efficiency and adopting low carbon fuels are the strategies with the greatest potential for achieving high GHG reductions in the transportation sector [48,49].

GHG emissions can also be reduced during the operation phase through the use of solar power or light-emitting diode (LED) lights that replace conventional lamps. Another option would be to reduce water consumption for roadside-plant irrigation. This can be achieved by using plant species that require less water, using smart irrigation systems, or using soil amendment to increase soil water capacity.

While this paper focuses on exploring options to reduce GHG emissions produced during the road construction and traffic operation phases, emissions can also be reduced during other phases. For example, during the rehabilitation and the maintenance phases, emissions can be reduced by minimizing the use of imported material for rehabilitation and maintenance through the use of in-situ cold recycling or reclaimed asphalt pavement. Xiao et al. [50] found that energy saving, GHG emission reduction, and cost-saving can be achieved through the implementation of reclaimed asphalt pavement. Meanwhile, adopting a proper maintenance program may also increase the service life of the road and consequently reduce the annually emitted GHGs over the life cycle of the project. Moreover, treatment of the road surface layers with rejuvenators may significantly increase the life span of a road [23]. However, rejuvenators are not fully established and applied yet [23], but as their use is developed further, their impact on reducing GHG emissions could be assessed more accurately.

2.5.2. Scenarios Selection

In this study, a number of scenarios with the potential to reduce GHG emissions in Abu Dhabi were selected and classified into two groups: those of relevance to municipalities and those of relevance to transport authorities. The first group includes road works during the construction phase as well as road lighting and irrigation during the road operation phase. The second group includes options for traffic management.

Although there is not yet a formalized procedure for the integration of GHG reduction in road projects in the UAE, there are initiatives such as those of "Estidama" and the Abu Dhabi Sustainable Roads Rating System (ADSRRS) that can be utilized as a guide for achieving this purpose. The Abu Dhabi Urban Planning Council (ADUPC) initiated Estidama (which means sustainability in Arabic) to transform the emirate into a model of sustainable urbanization and to endorse greener building standards. This initiative was designed to keep the physical, cultural, and traditional aspects of the region while applying sustainable measures. In addition to these features, Estidama has a unique rating system, called "the Pearl rating system", specifically tailored to fit the conditions of Abu Dhabi. It gives guidance from design through construction to operation stages of a project, taking into consideration the environmental, social, cultural, and economic pillars of sustainability [51]. On the other hand, the Abu Dhabi Department of Municipal Affairs identifies best practices for applying sustainable policies and measures to road projects through the ADSRRS, along with clarifying the appropriate guidelines to be followed. As the ADSRRS is an initial start in developing a comprehensive rating system for road projects, it can then be used over time to score performance in applying sustainable best practices to projects.

The selection of the explored scenarios was guided by the above sustainability initiatives and findings from the literature. The explored scenarios were also selected based on their potential adoption in Abu Dhabi in the short–medium term (i.e., within the coming 15 years). Thus, key factors in selecting some of the scenarios, whether they are available to use and apply, are not still in the research or development stage, and the extent to which a proposed scenario could be achieved within the short–medium term. For example, assuming total replacement of ICEVs with EVs may not be achievable in the coming decade since ICEVs are long-lived, there is a need for EV-related infrastructure, and EVs are not affordable by many. However, a lower EV adoption level of 10% may be possible.

Another guiding factor in the selection of the explored scenarios is related to the extent to which an activity contributes to GHG emissions. For example, results of the baseline cases showed that traffic movement during the operation phase contributes 80% to 97% of GHG emissions, while emissions during the construction phase account for only 1.8% to 6.5% of the total emissions of a road life cycle, and the rest of the emissions are mainly attributed to road lighting and plant irrigation [16]. Thus, it is expected that a reduction of emissions from vehicular traffic would have a higher overall impact on GHG emission reduction as compared to reduction of emissions generated during road construction. Nonetheless, it is still worth devoting effort to assessing the impact of reducing emissions from road construction activities, as they can offer opportunities for recycling waste material, reducing used resources, and meeting future targets for emission reduction set by local authorities. In fact, road construction GHG emissions are growing rapidly due to major ongoing road programs aiming to support economic development [52].

In total, fourteen scenarios were explored in this study. Five scenarios are related to the use of innovative techniques and approaches in road infrastructure construction. These five scenarios targeted road works (Table 3) and were found to contribute the most to GHG emissions during the construction phase [16]. Four scenarios are related to road lighting and water management during the operation phase, and the remaining five are related to traffic movement during the operation phase. Table 4 lists the explored scenarios, while a detailed description of these scenarios is presented below.

Table 4. Description of the explored GHG emission reduction scenarios along with the affected baseline categories.

| Scenario ID | Description | Affected Baseline Category |
|-------------|---|----------------------------|
| S1 | Use 15% recycled asphalt | Road works |
| S2 | Use 50% recycled aggregate | Road works |
| S3 | Replace hot-mix asphalt with warm-mix asphalt | Road works |
| S4 | Replace 70% PC with GGBFS for structural components | Road works |
| S5 | Use asphalt with a high stiffness modulus in the base layer | Road works |
| S6 | Replace conventional lamps with LED lamps | Road lighting |
| S7 | Use 25% solar energy for lighting | Road lighting |
| S8 | Reduce water consumption by 20% | Road-plant irrigation |
| S9 | Use 100% TSE for road-plant irrigation | Road-plant Irrigation |
| S10 | Reduce passenger car traffic by 10% | Traffic movement |
| S11 | Increase higher efficiency passenger cars by 10% | Traffic movement |
| S12 | Use LNG for 20% of passenger cars | Traffic movement |
| S13 | Replace 10% of ICE passenger cars with BEVs | Traffic movement |
| S14 | Replace 30% of ICE passenger cars with BEVs and change energy mix | Traffic movement |

Scenario S1 applies 15% of recycled asphalt. This percentage was adopted from Frigio et al. [53], who suggested that this is the current upper limit for the use of recycled asphalt in pavement. In this case, the quantity and transportation of asphalt reported by Alzard et al. [16] were reduced by 15%. For the reduced quantity, only GHG emissions related to transportation of material to the construction site were considered, since the effects of material extraction, processing, and removal have already been accounted for by another project (indirect emissions). Transportation of the reduced quantity was assumed to occur from Al Dhafra Industrial Facility in Abu Dhabi, which is almost 82 km away from Case 1 and 70 km from Cases 2 and 3.

Scenario S2 explores the option of using 50% recycled aggregate, which is the upper limit set by ADM. Similar to Scenario S1, the quantity of aggregate, as reported by Alzard et al. [16], was reduced by 50%. For this reduced rate, only the transportation effect was considered, since material extraction and processing have already been considered by another project. Recycled aggregates were assumed to be brought from Al Dhafra

Industrial Facility, whereas raw aggregates were brought from Al Fujairah Emirate with a roundtrip of 500–600 km from the project sites.

In Scenario S3, hot-mix asphalt used in the baseline case studies was replaced with warm-mix asphalt. As a result, the emission factor of processing asphalt was changed, but the transportation effect remained the same. According to Blankendaal et al. [26], a 30% reduction in emissions is achieved by adopting warm-mix asphalt. Hence, the emission factor for asphalt processing was reduced by 30% when applying this scenario.

In Scenario S4, the PC used in the concrete mix used for structural purposes was replaced by a mix of 30% PC and 70% GGBFS. This was applied to Cases 1 and 3 but not to Case 2, since concrete mixtures used during the construction phase of Case 2 utilized GGBFS as a replacement of a portion of PC. According to Tait and Cheung [29], the use of a concrete mix with 30% PC and 70% GGBFS would lead to a 60% reduction of GHG emissions. Thus, in applying this scenario, the emission factor associated with processing concrete used for structural purposes was reduced by 60%.

Scenario S5 is related to the use of asphalt with a high stiffness modulus in the base layer. Researchers found that this would reduce the layer thickness by 25% [23]. Thus, by adopting this scenario, the quantity of the materials used for the base layer was reduced by 25%, resulting in lower emissions due to reduced material usage and transportation.

Scenarios S6 and S7 are related to better management of road lighting. In Scenario S6, conventional lamps currently used in the studied cases were replaced by LED lamps. Several studies reported that switching from conventional to LED lamps would reduce energy consumption by about 40% [23,54,55]. Other studies reported an even higher energy reduction (60%) when specific conditions were satisfied [56]. In exploring this scenario, the amount of fuel consumed to generate electricity for lighting was reduced by 40%.

Scenario S7 explores the option of replacing 25% of fuel-generated electricity for lighting with solar-generated energy. Road lighting is exclusively used at night, while solar power is exclusively produced during the day. This mismatch raises the need for energy storage facilities. Energy storage facilities often rely mainly on lithium-ion batteries. The production of lithium-ion batteries produces a significant amount of emissions. In addition, there is an efficiency problem associated with solar energy production. That is, only a fraction of the solar energy is converted into electricity. This creates a need for increased energy production capacity, which in turn translates into emissions related to significant solar panel production. Nonetheless, in this study, emission reduction related to the use of solar energy for road operation lighting was considered. Jungbluth et al. [57] used Ecoinvent and found that photovoltaic (PV) electricity emission rates for different countries range from 0.046 to 0.084 kg CO_2e/kWh . In this study, the upper value was used as a conservative estimate of the rate of emissions associated with the use of solar-powered PV panels in Abu Dhabi, since almost 100% of the power produced in the UAE is produced by fossil fuels, more specifically, natural gas. As such, the emission factor associated with 25% of fuel-generated electricity was reduced from 1.0389 kg CO₂e/kWh [58] for the baseline conditions to $0.084 \text{ kg CO}_2\text{e}/\text{kWh}$.

Scenarios S8 and S9 are related to water usage in road irrigation. Scenario S8 assumes a reduction of 20% in water consumption for irrigation due to the adoption of water conservation initiatives. GHG emission calculations for the baseline conditions were carried out assuming that 75% of the water used in road landscape irrigation is TSE while the remaining 25% is desalinated water [16]. The proposed reduction was applied to the amount of desalinated water (EF = $0.02158 \text{ kg CO}_2\text{e/L}$ [59]) used, since it has a higher environmental impact than that of TSE (EF = $0.0001475 \text{ kg CO}_2\text{e/L}$ [44]). On the other hand, Scenario S9 assumes full utilization of TSE for the irrigation of green landscapes.

Scenarios S10–S14 were selected to investigate the possibility of reducing emissions from traffic operations by changing the traffic characteristics of passenger cars. In Scenario S10, the passenger car traffic was reduced by 10%. This scenario is straightforward, and entails reducing the number of each type of passenger cars (two-seater, mini-compact, subcompact, compact, mid-size, full-size, small station wagon, and mid-size station wagon)

by 10%. In a similar manner, in Scenario S11, 10% of the passenger cars were replaced by more fuel-efficient ones, in terms of fuel consumption rate. For example, a 2014 model station wagon with a fuel consumption rate of 0.0799 L fuel/km was replaced by a value of 0.0716 L fuel/km for the 2018 model, thus reducing the amount of fuel consumed per kilometer travelled. In Scenario S12, 20% of the passenger cars that originally operated by gasoline were replaced by passenger cars that use LNG. Since LNG has a lower emission factor (1.436 kg CO_2e/L) compared to gasoline (2.384 kg CO_2e/L), a drop in emissions due to applying this scenario would be expected.

Scenario S13 was selected to investigate the impact of replacing ICEVs with BEVs on emission reduction. It was assumed that a 10% replacement would occur. However, it was expected that this 10% replacement would occur within the passenger car vehicle class only, as this is the only vehicle class in which BEVs have been adopted on a meaningful scale due to battery and cost issues [60]. Although replacing 10% of the internal combustion engine (ICE) passenger cars with battery electric (BE) passenger cars might seem to be a low adoption rate, it is much higher than the current global adoption rate of only 1% [61]. Furthermore, it is important to consider barriers that have the potential to prevent a largerscale shift from ICEVs to BEVs in Abu Dhabi in the medium term. For example, gasoline prices in Abu Dhabi are significantly lower than those in many European countries, BEVs have a higher purchase cost relative to ICEVs [62], and gasoline vehicles are long-lived [63]. Thus, unless the Abu Dhabi government adopts policies to incentivize BEV uptake [64], these barriers may prevent ICEV owners from switching to BEVs at a faster pace.

Different passenger cars have different fuel efficiency levels. In addition, Abu Dhabi's hot weather may lower BEVs' efficiency levels [65] and, therefore, lower driving ranges as well as emission reduction levels. S13 was modelled based on electricity consumption levels pertaining to one of the most largely sold electric vehicles, the Nissan Leaf. As such, a city-based consumption of 0.111 kWh/km was assigned to Case 1 (Al Rahba City), while a consumption of 0.144 kWh/km was assigned to Cases 2 and 3 (Al Salam Street and Corniche Road) [66]. Fuel efficiency levels (in L fuel/km) of ICE passenger cars, light trucks, and heavy trucks were determined as a weighted average based on vehicle models included in the traffic counts provided by ADM. As such, the fuel efficiency of ICE passenger cars, light trucks, and heavy trucks for Case 1 was 0.1179, 0.1536, and 0.35, respectively. Fuel efficiency of ICE passenger cars, light trucks, and heavy trucks for Case 2 was 0.1036, 0.1366, and 0.30, respectively. Fuel efficiency of ICE passenger cars, light trucks, and heavy trucks for Case 3 was 0.1013, 0.1536, and 0.35, respectively.

In S13, the average emissions estimation method was utilized to determine the amount of carbon emitted by the power sector. Though output from the average emissions estimation method might not be as accurate as output from the marginal emissions method (depending on factors such as energy mix and electricity consumption timing), the adoption of the average emissions method may be a reasonable approach in the context of power systems where the dispatchable energy is generated from one source [67]. In Abu Dhabi, 85% and 13% of the electricity are currently produced by combined-cycle and open-cycle natural gas power plants, respectively. The remaining 2% is produced by solar energy [68,69]. Heat rates of thermal plants as well as carbon emission factors for natural gas fuel were obtained from Elshurafa and Peerbocus [70].

Finally, an alternative scenario to S13 (S14), based on Abu Dhabi's 2035 planned energy mix and a higher BEV adoption rate, is also discussed. This futuristic scenario was based on (i) a future energy mix consisting of 26%, 34%, and 40% of solar, gas, and nuclear energy, respectively [68,69] and (ii) increased replacement of ICE passenger cars with BE passenger cars from 10% to 30%. To model this scenario, a few assumptions had to be made. First, the solar energy would be consumed during the daytime. This would not only eliminate the need for energy storage facilities, but it would also simplify the distribution of electricity consumed by BEVs per energy source. Second, future power grid capacity could accommodate additional electricity demand from BEV charging [71]. Third, BEVs would be charged during off-peak times (i.e., late at night and early in the morning) only under a controlled scenario [72]. This assumption would eliminate the need to determine BEV electricity consumption based on random charging times (though this would be a more realistic scenario once Abu Dhabi has proper BEV-related infrastructure in place). Thus, assuming that BEVs would be charged during off-peak times only and that solar energy would be consumed during the daytime, BEVs would consume electricity produced either by natural gas or nuclear power. Finally, since it is expected that 26%, 34%, and 40% of the electricity consumed in Abu Dhabi by 2035 will be produced by solar energy, natural gas, and nuclear energy, respectively, 54.05% and 45.95% of the electricity consumed by BEVs during off-peak times would be produced by nuclear energy and natural gas, respectively. Considering that power companies would prioritize operating their plants with lower operating costs first (i.e., nuclear as opposed to gas power plants), it would be reasonable to assume that nuclear energy would produce the baseload power and, therefore, the electricity consumed by BEVs would come from dispatchable power produced by gas power plants. The implications of this alternative scenario are discussed in Section 3.3.2. Altering any of the assumptions previously described would surely change emission reductions. For example, previous research has shown that BEV charging times may have an impact on the effectiveness of BEVs on reducing system-wide carbon emissions, depending on the energy mix used to power the grid [35].

It is important to stress that this study focused solely on tailpipe emissions and that it was not the purpose of this study to investigate life-cycle emissions. Therefore, this study rather focused on the local (i.e., within the boundaries of each one of the three case studies analyzed) emission reduction impact that the replacement of a portion of ICE passenger cars with BE passenger cars would have. This is an important consideration, since previous studies have shown that a large portion of the emissions associated with BEVs are produced upstream (e.g., during battery production) [36]. These upstream emissions may likely be even more significant when the effect of extreme temperature is considered [65]. That is, in environments in which extremely high temperatures are the norm (as is the case in Abu Dhabi during most of the year), the expected lifetime of the batteries may be reduced. Therefore, it is likely that the emission reduction presented in this paper is larger than what it would have been had upstream emissions produced during the battery manufacturing phase (coupled with extreme weather impact during the vehicle operation phase) been considered. Another point to stress is that the assumption made in this study that nuclear power will be the source of electricity for 40% of Abu Dhabi's electricity in the future is merely based on Abu Dhabi's already-announced future energy mix plans [68]. Nuclear power currently produces 10% of the world's energy [73] and is a carbon-free energy source, which, due to its non-intermittent nature, can be effective in reducing carbon emissions. However, nuclear power usage results in the generation of nuclear waste, which can remain radioactive for a long time and, therefore, may threaten the safety of human lives and the environment. Methods intended to safely handle nuclear waste have been implemented for some time now, but some of these methods have been seen as not only unsafe, but also as short-term oriented [74,75]

3. Results and Discussion

3.1. Potential GHG Emission Reduction through Road Works and Road Municipal Services 3.1.1. Road Works

Table 5 shows the effect of the employed scenarios of reducing GHG emissions associated with road works (S1 to S5) for the three road cases. The baseline emissions associated with road works in ton CO_2e for the three road cases are 15,372, 61,236, and 8910, respectively (Table 3). The extremely high emissions associated with the road works of Case 2 are mainly attributed to the use and transportation of concrete and steel needed to construct the 0.6 km tunnel and other concrete structures on this road, in addition to the emissions originating from earthwork [16].

| Scenario | Case 1 | | Case 2 | | Case 3 | |
|----------|-----------|---------------|-----------|---------------|-----------|---------------|
| | Emissions | Reduction (%) | Emissions | Reduction (%) | Emissions | Reduction (%) |
| Baseline | 15,372 | - | 61,236 | - | 8910 | - |
| S1 | 15,366 | 0.04 | 61,057 | 0.29 | 8812 | 1.10 |
| S2 | 15,364 | 0.05 | 61,007 | 0.37 | 8882 | 0.31 |
| S3 | 15,348 | 0.16 | 60,472 | 1.25 | 8516 | 4.42 |
| S4 | 14,720 | 4.24 | NA | NA | 7743 | 13.10 |
| S5 | 15,225 | 0.96 | 60,765 | 0.77 | 8765 | 1.63 |
| S1 to S5 | 14,682 | 4.49 | 59,769 | 2.40 | 7149 | 19.76 |

Table 5. Road works emissions (ton CO_2e) under the explored reduction scenarios along with the emission reduction relative to the baseline conditions of the category.

In Scenario S1, 15% of recycled asphalt is used in the three case studies. Adoption of this scenario leads to a decrease in emissions from pavement construction by 1.0% to 3.2%. As such, road works emissions are reduced by 0.04% to 1.10% (Table 5). When 50% recycled aggregate was used for the three studied cases (Scenario S2), a decrease in pavement emissions of 1.17%, 3.9%, and 0.52% was achieved in Cases 1, 2, and 3, respectively. The above numbers translate into a very low overall impact on road works emission reduction that does not exceed 0.37% (Table 5). However, replacing hot-mix asphalt with warm-mix asphalt (S3) for the three case studies reduces pavement emissions by 3.4% to 14.6%, which corresponds to a respective road works emission reduction of 0.16% to 4.42% (Table 5).

In Scenario S4, replacing 70% of PC used in concrete mix with GGBFS for Cases 1 and 3 causes a high (37% to 51%) reduction in the emissions associated with concrete works. Subsequently, a 4.24% to 13.10% decrease in the road works emissions of these cases is achieved (Table 5). For Case 2, this scenario is not applicable (NA), since GGBFS was used in the concrete mix of the road works of this case.

In Scenario S5, the thickness of the asphalt base layer is reduced by 25% by using asphalt with a high stiffness modulus. As a result, emissions due to pavement construction are reduced by 5.0% to 8.0%, which corresponds to an overall reduction in road works emissions of 0.77% to 1.63% (Table 5).

Based on the scenarios related to road works (S1 to S5), the highest reduction in emissions is in the use of GGBFS as a partial replacement of PC in concrete work (S4). For the S4 scenario, the impact is more pronounced for Case 3 as compared to Case 1, since the construction of primary roads usually requires more concrete than that of secondary roads. The second scenario that showed appreciable emission reduction is replacing hot-mix asphalt with warm-mix asphalt, especially for primary roads (Cases 2 and 3). On the other hand, the use of 15% recycled asphalt (S1) or 50% recycled aggregate (S2) shows the least emission reductions among the scenarios associated with road works. It is also noticed that for a given scenario, the emission reductions for the primary road case (Case 1). This is because the selected scenarios are related to the materials used during construction and not to emissions from the use of construction equipment. For Case 1, the contribution of emissions from materials is 30% as opposed to 70% from equipment [16]. However, for Cases 2 and 3, the contribution of materials to emissions during the construction phase is 80% or more [16].

While the above results focused on the individual effect of each scenario, one may consider combined scenarios to achieve a higher reduction in GHG emissions. In this case, the reduction in GHG emissions for the combined scenarios may not necessarily be the sum of the effect of the individual ones, as some scenarios may not be completely independent of others. For example, the use of asphalt with a high stiffness modulus in the base layer (S5) would reduce the thickness of the base layer, and when coupled with the use of 50% recycled aggregate (S2), would result in a different quantity of recycled aggregate as compared to the quantity when S5 is not adopted. Table 5 lists the results of

combined scenarios S1 to S5 for the three case studies. When combined, the emissions due to road works are reduced by 2.40% to 19.76%.

3.1.2. Road Municipal Services

Road municipal services are those provided by municipalities during the operation phase of a road project life cycle. They include road lighting, roadside-plant irrigation, stormwater management, and road cleaning. Results of emission reduction scenarios pertinent to road lighting and roadside-plant irrigation are presented in this section. No emission scenarios were proposed for stormwater management due to the insignificant contribution of this activity to GHG emissions during a road project life cycle in Abu Dhabi Emirate [16]. Furthermore, no emission scenarios were proposed to reduce emissions associated with road cleaning, as emissions from such an activity were not estimated for the baseline conditions.

Table 6 shows the effect of the employed scenarios in reducing GHG emissions associated with road lighting (S6 and S7) for the three road cases. The baseline emissions associated with road lighting in ton CO_2e/y for the three cases are 2045, 5318, and 213, respectively (Table 3). The high emissions associated with road lighting in Case 2 are mainly due to the continuous lighting of the 0.6 km tunnel in a 3.6 km road segment.

Table 6. Emissions (ton CO_2e/y) under the explored reduction scenarios of road lighting and roadside-plant irrigation along with the emission reduction relative to the baseline conditions of their category.

| Scenario – | Case 1 | | Case 2 | | Case 3 | |
|------------|-----------|----------------------|-----------|----------------------|-----------|----------------------|
| | Emissions | Reduction (%) | Emissions | Reduction (%) | Emissions | Reduction (%) |
| Baseline | 2045 | - | 5318 | - | 213 | - |
| S6 | 1227.0 | 40.0 | 3190.8 | 40.0 | 127.8 | 40.0 |
| S7 | 1575.1 | 23.0 | 4096.0 | 23.0 | 164.1 | 23.0 |
| S6 and S7 | 945.1 | 53.8 | 2457.6 | 53.8 | 98.4 | 53.8 |

In Scenario S6, conventional light bulbs are replaced by LED lamps for the three cases. A reduction of 40% in emissions due to road lighting is achieved for each of the three cases. Additionally, a reduction of emissions is attained under Scenario S7 in which 25% of solar energy is utilized for road lighting. In this case, a reduction of 23% in emissions due to lighting is achieved for each case. When combined, the two scenarios result in about 54% reduction of emissions associated with road lighting for each case.

Table 7 shows the effect of the employed scenarios in reducing GHG emissions associated with roadside-plant irrigation (S8 and S9) for the three road cases. The baseline emissions associated with roadside-plant irrigation are 152, 59, and 10, respectively (Table 3). In Scenario S8, a reduction of 20% of water consumed by roadside-plants causes 78.4% emission reduction in each of the considered road cases. This significant emission reduction occurred because the reduced water volume was entirely subtracted from desalinated water. A higher emission reduction of about 97.3% is achieved under Scenario S9 in which 100% TSE is used. When combined, the two scenarios result in about 98% emission reduction associated with this activity.

Table 7. Emissions (ton CO_2e/y) under the explored reduction scenarios of road lighting and roadside-plant irrigation along with the emission reduction relative to the baseline conditions of their category.

| Scenario - | Case 1 | | Case 2 | | Case 3 | |
|------------|-----------|----------------------|-----------|----------------------|-----------|----------------------|
| | Emissions | Reduction (%) | Emissions | Reduction (%) | Emissions | Reduction (%) |
| Baseline | 152 | - | 59 | - | 10 | - |
| S8 | 32.8 | 78.4 | 12.7 | 78.4 | 2.2 | 78.4 |
| S9 | 4.1 | 97.3 | 1.6 | 97.3 | 0.3 | 97.3 |
| S8 and S9 | 3.3 | 97.9 | 1.3 | 97.9 | 0.2 | 97.9 |

3.2. Traffic Volume Reduction, Fuel Efficiency Improvement, LNG Usage Increase, and Replacement of ICEVs with BEVs

Table 8 shows the effect of the employed scenarios in reducing GHG emissions associated with traffic movement (S10 to S14) for the three road cases. The baseline emissions associated with traffic movement in ton CO_2e/y for the three road cases are 13,345, 102,610, and 22,504, respectively (Table 3).

Table 8. Emissions (ton CO_2e/y) under the explored reduction scenarios of traffic management along with the emission reduction relative to the baseline conditions of the category.

| | Case 1 | | Case 2 | | Case 3 | |
|--------------------|-----------|---------------|-----------|------------------|-----------|------------------|
| Scenario | Emissions | Reduction (%) | Emissions | Reduction (%) | Emissions | Reduction (%) |
| Baseline | 13,345 | - | 102,610 | - | 22,504 | - |
| S10 | 13,006 | 2.54 | 100,177 | 2.37 | 21,974 | 2.36 |
| S11 | 13,344 | 0.01 | 102,515 | 0.09 | 22,481 | 0.11 |
| S12 | 12,848 | 3.72 | 100,668 | 1.89 | 22,081 | 1.88 |
| S13 | 13,150 | 1.46 | 103,165 | -0.54 | 22,497 | 0.03 |
| S14 | 12,715 | 4.72 | 96,428 | 6.02 | 21,110 | 6.19 |
| S10 to S13 | 12,343 | 7.51 | 98,782 | 3.73 | 21,533 | 4.32 |
| S10 to S12 and S14 | 11,908 | 10.77 | 92,045 | 10.30 | 20,146 | 10.48 |

In Scenario S10, reducing the number of passenger cars by 10% results in a 2.54%, 2.37%, and 2.36% emission reduction in Cases 1, 2, and 3, respectively due to vehicle movement. In Scenario S11, increasing the use of higher efficiency passenger cars by 10% reduces emissions due to vehicle movement by 0.01%, 0.09%, and 0.11% in Cases 1, 2, and 3, respectively. In Scenario S12, increasing the use of passenger cars fuelled by LNG by 20% results in a 3.72%, 1.89%, and 1.88% emission reduction in Cases 1, 2, and 3, respectively. Thus, S10 and S12 are more effective in reducing emissions as compared to S11.

In Scenario S13, replacing 10% of the ICE passenger cars with BE passenger cars resulted in a 1.46% and 0.03% emission reduction in Cases 1 and 3, respectively, but a 0.54% emission increase in Case 2. This suggests that replacing ICEVs with BEVs in a scenario in which electricity is produced by natural gas may result in no significant emission reduction, or even in an emission increase in scenarios where ICEVs are more fuel-efficient (e.g., Case 2). However, in Scenario S14, replacing 30% of the ICE passenger cars with BE passenger cars and having half of the electricity consumed by BEVs produced by a clean source (i.e., nuclear power), while still having the remaining half of the electricity consumed by BEVs produced by natural gas, resulted in a 4.72%, 6.02%, and 6.19% emission reduction in Cases 1, 2, and 3, respectively. This suggests that significant emission reduction should be expected when BEVs are powered by clean energy sources. However, when nuclear power is used mainly as a baseload power source while natural gas is used mainly as a dispatchable power source, then the results of such scenario were found to be similar to those observed in S13, since BEVs will likely be powered mainly from the dispatchable power source (i.e., natural gas).

When the combined emission reductions from S10–S13 were considered, it was found that emissions are reduced by about 7.5% for secondary roads (Case 1) and by about 4% for primary roads (Case 2 and 3). The combined emission reductions from S10–S12 and S14 were found to be even larger, resulting in about 10% emission reduction in each of the considered cases.

3.3. Discussion

3.3.1. Emission Reduction through Road Works and Municipal Road Services

Based on the selected emission reduction scenario, normalized emission reduction for the three road cases was estimated for activities of relevance to municipal work (i.e., road works, road lighting, and roadside-plant irrigation). For normalization, annual emissions for road works under the selected scenarios were estimated assuming a 40-year road service lifetime [16]. Since the three road cases differ in their lengths, emissions were normalized for comparative analysis per 1 m unit paved length. For the baseline conditions, the normalized emissions for the combined road works, road lighting, and roadside-plant irrigation are 86, 1919, and 155 kg CO₂e/m/y for Cases 1–3, respectively. By benchmarking these values to those reported by others, Alzard et al. [16] concluded that the normalized emissions for Case 1 and 3 are three to four times higher than those reported for some European countries [23,76]. However, the normalized emissions were found to be 32 times higher for Case 2. The contribution of each activity to the total emissions of the three activities is presented in Figure 2. For the three cases, road lighting is a significant contributor to the total emissions, which may be explained by the fact that almost all Abu Dhabi roads are lit, even rural facilities. Road lighting was then followed by road works as a significant contributor to the total emissions. The contribution of roadside-plant irrigation to the normalized emissions did not exceed 6% in any of the cases.



Figure 2. Relative contribution of road works, road lighting, and roadside-plant irrigation to the emissions of the studied cases.

The reduction in the normalized emissions associated with municipal road activities under the explored scenarios in this study is shown in Figure 3. As evident from Figure 3, the scenarios that could have a major impact on reducing GHG emissions of road works and municipal road services in Abu Dhabi are those related to road lighting (S6 and S7). For example, replacing conventional lamps with LED lamps (S6) reduces the emissions for Case 1 and Case 3 by 27 and 30 kg CO₂e/m/y, respectively. The impact of this measure is more profound for Case 2, where emissions are reduced by 591 kg CO₂e/m/y. Using 25% solar energy for lighting (S7) also has a significant impact on emission reduction, although it is less effective than S6. In adopting S7, emissions are reduced for Case 1, Case 2, and Case 3 by about 16, 339, and 17 kg CO₂e/m/y, respectively. When the two scenarios are combined (S6–S7), the respective emissions for Case 1–3 are reduced by about 37, 795, and 40 kg CO₂e/m/y, which corresponds to a reduction of 26–43% of emitted GHGs during road works, road lighting, and roadside-plant irrigation.

The impact of the explored measures related to roadside-plant irrigation (S8 and S9) is lower than those of road lighting despite the high impact of these scenarios on the activity itself (Table 7). The combined effect of reducing water by 20% (S8) and using 100% TSE (S9) for roadside-plant irrigation causes a reduction of 3 to 16 kg $CO_2e/m/y$, which is equivalent to a reduction of 1–6% of emitted GHGs during road works, road lighting, and roadside-plant irrigation. On the other hand, using GGBFS as a partial replacement of PC in structural concrete (S4) is the most effective measure among those explored for road works, as it reduces emissions by about 10 kg $CO_2e/m/y$. This is followed by an emission reduction of about 3–5 kg $CO_2e/m/y$ for the primary road cases when hot-mix asphalt is replaced by warm-mix asphalt (S3). The other suggested road works scenarios of using 15% recycled asphalt (S1), using 50% recycled aggregate (S2), and using asphalt with a high stiffness modulus in the base layer (S5) do not result in a significant emission reduction. Nonetheless, the adoption of these scenarios could be beneficial in not only adding to the total reduced emissions, but also in saving resources and in recycling waste material. Recycling waste material in road construction contributes to the circular economy model of sustainable development by providing low-cost products as well as promoting a healthier environment. When all scenarios (S1–S9) are applied, the reduction in the emissions for Case 1–3 are 42, 821, and 59 kg $CO_2e/m/y$, respectively. This is equivalent to a 38–50% reduction of emissions associated with road works and road municipal services.



Figure 3. Emission reductions associated with the explored individual and combined scenarios related to road works (S1 to S5), road lighting (S6 and S7), and road-plant irrigation (S8 and S9).

3.3.2. Emission Reduction through Traffic Volume Reduction, Fuel Efficiency Improvement, LNG Usage Increase, and Replacement of ICEVs with BEVs

Although some of the explored scenarios related to traffic movement (S10–S13) did not result in large emission reductions, on a percentage basis, relative to baseline emissions (Table 8), emission reduction produced by these scenarios is significant, on an absolute basis, considering that the amount of emissions produced during the operation phase is significantly larger than that produced by road works, lighting, and roadside-plant irrigation. Figure 4 shows that reducing passenger cars by 10% (S10) results in a reduction of 11 kg $CO_2e/m/y$ for secondary roads (Case 1) and 185–676 kg $CO_2e/m/y$ for primary roads (Cases 2 and 3). Similarly, increasing LNG usage by passenger cars by 20% (S12) results in a reduction of 17 kg $CO_2e/m/y$ for secondary roads and 148–539 kg $CO_2e/m/y$ for primary roads. In fact, the emission reduction achieved by adopting Scenario S10 or S12 is comparable to that of S1–S9 combined (Figure 3). The replacement of 10% of the ICE passenger cars with BE passenger cars (S13) resulted in minimal emission reduction for Case 3 and in negative emission reduction for Case 2. However, when the BEV scenario was expanded based on Abu Dhabi's 2035 energy mix plan (i.e., considering that 54% and 46% of the power produced to meet BEV demand would come from nuclear and gas power plants, respectively), as well as on a BE passenger car adoption rate of 30% (S14), it was found that emissions would be reduced by 4.72%, 6.02%, and 6.19% in Cases 1, 2, and 3, respectively. When all explored traffic movement scenarios (S10–S13) were combined, overall GHG emissions reductions of 33, 1063, and 338 kg $CO_2e/m/y$ were achieved. This corresponds to an emission reduction of 3.7–7.5% of emissions associated with traffic movement. When S13 was replaced by S14, overall GHG emission reductions due to traffic movement scenarios of 48, 2935, and 822 kg $CO_2e/m/y$ were achieved, which corresponds to a reduction of about 10% of emissions associated with traffic movement.



Figure 4. Emission reductions associated with the explored individual and combined scenarios related to traffic movement (S10 to S14).

3.3.3. Overall Emission Reduction

When all the scenarios (S1–S12 and S14) are considered, emissions (in kgCO₂e/m/y) are reduced by 90 for secondary roads (Case 1), 3756 for primary roads with major structures (Case 2), and 880 for the widening of primary roads (Case 3). This corresponds to an overall reduction of about 17%, 13%, and 9% of the GHGs emitted during the life cycle of the respective road cases. Out of these emission reductions, traffic management measures (S10–S12 and S14) contribute the most (53–93%), followed by lighting measures (replacing conventional lamps with LED lamps and using 25% solar energy for lighting) with a share of 5–41% of the emission reduction. The contribution of road works emission reduction scenarios (S1–S9) to the normalized emission reduction is very low (0.6–8%). Despite that, emission reduction measures from road works should not be ignored, as they may offer opportunities for recycling waste products and saving resources.

Under all scenarios, the normalized emission reductions for the two primary road cases show that the reductions for Case 2 are much higher than those of Case 3 for any scenario. This is mainly because of the higher number of lanes for Case 2 (eight lanes) as compared to that of Case 3 (two lanes). In addition, any similar positive percentage reduction in road works and road services for the two cases translates into a higher emission reduction in Case 2 due to the presence of major concrete structures (a tunnel and interchanges). A comparison between Case 1 and 3 (both have two lanes) shows that, for most of the explored scenarios, the normalized emission reductions in Case 3 (primary road) are much higher than their counterparts in Case 1 (secondary road). This is attributed to higher traffic movement on primary roads and differences in the design of the two types of roads. Thus, it can be inferred from the above discussion that emphasis on emission reduction measures should focus on primary roads, since these roads presented a higher emission reduction potential on a normalized basis.

4. Conclusions

This paper assessed the potential of 14 mitigation scenarios on GHG emission reduction during the road project life cycle. These scenarios were applied to three different road projects located in Abu Dhabi city. The explored scenarios focus mainly on emission reduction for activities related to road works, road lighting, roadside-plant irrigation, and traffic movement. These scenarios either altered the activity data or the emission factor associated with the activity.

Findings reveal that normalized GHG emissions produced by road projects are reduced relative to baseline conditions, in decreasing order of magnitude, by (i) replacing 30% of ICE passenger cars with BEVs when power demand was almost equally produced by nuclear and natural gas plants, (ii) reducing the number of passenger cars by 10%, (iii) having one-fifth of passenger cars powered by LNG, (iv) replacing conventional lamps with LED lamps, (v) having one-fourth of road lighting powered by solar energy, (vi) replacing a portion of PC with GGBFS, (vii) fully utilizing TSE for roadside-plant irrigation, (viii) reducing desalinated water used for roadside-plant irrigation by 20%, (ix) increasing fuel efficiency of passenger cars by 10%, and (x) replacing hot-mix asphalt with warm-mix asphalt. Explored scenarios of using 15% recycled asphalt, using 50% recycled aggregate, and using asphalt with a high stiffness modulus in the base layer have the least impact on emission reduction. These scenarios, however, may offer opportunities for recycling waste products and saving resources. Combining emission-mitigation measures during road works and road municipal services can reduce emissions from these activities by 38–50%, while emissions produced during the traffic operation phase can be reduced by about 10%. When all explored scenarios are combined, a significant, overall normalized GHG emissions reduction of 9–17% during the road project life cycle can be achieved.

Author Contributions: Conceptualization, M.A.M., R.C., F.D.B.A. and J.E.Z.; data curation, M.H.A. and L.A.K.; formal analysis, M.H.A., F.D.B.A. and M.A.M.; funding acquisition, M.A.M. and R.C.; investigation, M.A.M. and M.H.A.; methodology, M.H.A. and F.D.B.A.; project administration, M.A.M., R.C. and J.E.Z.; supervision, M.A.M. and R.C.; validation, M.A.M. and J.E.Z.; visualization, M.H.A.; writing—original draft, M.A.M. and F.D.B.A.; writing—review and editing, M.H.A., L.A.K. and J.E.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Abu Dhabi City Municipality, grant number 21R021.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are provided within the article.

Acknowledgments: In memoriam of Rezaul Chowdhury who passed away prior to submission of the manuscript. Special thanks go to Khaled N. Al Junadi and Shamsa Almuharrami from Abu Dhabi City Municipality and to Yasser Hawas from Emirates Center for Mobility Research, UAE University, for facilitating the work conducted in this study. Our thanks are also extended to the anonymous reviewers for their constructive comments on an earlier version of this manuscript.

Conflicts of Interest: The funder had no role in the design of the study, in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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