Technical Appendix

Methodologies, Assumptions, and Calculations

The methodologies used in the Photocatalytic Pavement Treatment Program Model (Table 1) for the Brevard County, City of Palm Bay Coalition followed the rigorous, systematic, and objective procedures under the Science-Based Targets protocol using the *best available science* from direct product testing by independent research universities; Environmental Protection Agency (EPA) estimates; and a wide array of literature on the subject matter. The model primarily relied upon direct product testing performed by the Texas A&M Transportation Institute (TTI) and the Purdue University Lyles School of Engineering (Purdue).

The following direct product tests were performed:

ISO 22197-3 – *Test Method for Air-Purification Performance of Semiconducting Photocatalytic Materials*	Texas A&M University[1] Louisiana State University[2]
ASTM E1980-11 – *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Surfaces*	Texas A&M University[3]
ASTM D7334-08 – *Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement*	Texas A&M University[4] [5] Massachusetts Institute of Technology
ASTM E1253 – *Infrared Organic Spectrometry*	Texas A&M University[6] [7]
Proprietary Carbon Dioxide Removal	Purdue University[8]
ISO 10678 – *Determination of Photocatalytic Activity or the Standard ("Self-Cleaning") Photocatalytic Test*	Purdue University[9]

[1] Zollinger DG and Joshaghani A, *Laboratory Investigation of the Effect of TiO_2 Topical Treatments on Concrete and Asphalt Samples*, Texas A&M Transportation Institute, September 2018.

[2] Hassan M, Dylla H, et al, *Durability and Performance of Titanium Dioxide in Photocatalytic Pavements*, Louisiana State University, 2011.

[3] Zollinger DG and Joshaghani A, *Solar Reflectance Analysis of TiO2 Penetrant Treatments on Concrete and Asphalt Samples*, Texas A&M Transportation Institute, August 2019.

[4] See 3.

[5] Arainpour F and Farzaneh M, On Hydrophobic and Icephobic Properties of TiO_2-Doped Silicon Rubber Coatings, Department of Applied Sciences, Universite du Quebec*, International Journal of Theoretical and Applied Nanotechnology*, 2012.

[6] Nabi I and Bacha A, et al., Complete Photocatalytic Mineralization of Microplastic on TiO_2 Nanoparticle Film, iScience, July 24, 2020.

[7] Zollinger D and Philip J, Effect of TiO_2 Topical Treatments on Concrete and Asphalt for On-Road Microplastic Pollution Removal, Texas A&M Transportation Institute, August 2022.

[8] Velay Lizancos, M, Garcia Lopez-Arias, M, et al, *Carbon Dioxide Removal w/ Titanium Dioxide Pavement Additives Progress Report,* Purdue University, November 2023.

[9] See 8.

The model incorporated the photocatalytic efficiencies as determined by the TTI and Purdue studies et al., and applied under the UN IPCC Fifth Assessment with the following exceptions:

- Nitrogen Oxides (NOx) [10]
- Solar Reflectance Index (SRI) [11]
- Vehicle RAMP (microplastics) [12]

The following research was also applied where applicable from the literature:

- Nowak D, U.S. Forestry Service: *Air Pollution Removal Capacity of Urban Forests*.
- Equivalent removal factor (EFR) between an urban tree and a photocatalytic surface, Heidelberg Cement Group.
- World Bank Carbon Market Analysis Report 2022.
- International Agency for Research on Cancer (IARC); California Office of Environmental Health Hazard Assessment (OEHHA), Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65).
- Ruszakla MJA, et al, Low Carbon Footprint TiO_2 Substitutes in Paint, *International Journal of Chemical Engineering and Applications*, October 2015, University of Utah, Materials Science & Engineering Department.
- Chehovits J and Galehouse L, *Energy Usage and Greenhouse Gas Emissions of Pavement Preservation Processes for Asphalt Pavements, Transportation Research Board*, 2010.
- Chemours (formerly DuPont) Ti-Pure paint coatings; Alcoa Architectural Coatings – TiO_2 enhanced EcoClean Aluminum Panels.
- de Dios J, del Campo JM et al, *Decontamination through Photocatalytic TiO_2 Additions – Past, Present and Future*, International Conference on Emerging Trends in Engineering and Technology (ICETET), London 2014.
- Zweigle J, Bugsel B et al, University of Tubingen, *PFAS precursor characterization via UV/TiO_2 photocatalysis*, 2022.
- Arainpour F and Farzaneh M, On Hydrophobic and Icephobic Properties of TiO_2-Doped Silicon Rubber Coatings, Department of Applied Sciences, Universite du Quebec, *International Journal of Theoretical and Applied Nanotechnology*, 2012.

[10] 60 Co_2e per Dahlmann K et al, *Quantifying the contributions of individual NOx sources to the trend in ozone radiative forcing*, DLR Institute for Atmospheric Physics, Oberpfaffenhofen, Germany, February 2011.

[11] Massachusetts Institute of Technology (MIT) – MIT Concrete Sustainability Hub (CSHub): Solar Reflectance Index (SRI) ASTM E1980-11 *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces*; converted into radiative forcing (RF) or GWP/ CO_2e.

[12] Shen M, Huang W, et al, (Micro)plastic crisis: Un-ignorable contribution to global greenhouse emissions and climate change, May 2020.

- Nabi I and Bacha A, et al., Complete Photocatalytic Mineralization of Microplastic on TiO_2 Nanoparticle Film, iScience, July 24, 2020.
- Wilcox J, Carbon Capture, *Springer*.
- *Polymers, Light and the Science of 7*, DuPont™ Ti-Pure® Titanium Dioxide, DowDuPont, www.dow-dupont.com.
- Gopalakrishnan K, et al., *Climate Change, Energy, Sustainability, and Pavements*, Springer, 2014.
- Hamilton Thorne, www.hamiltonthorne.com.
- WEF Institute of Technology, Inc., www.aoyama-wefit.com/en/faq/a18.html.
- www.optipurewater.com.
- National Asphalt Pavement Association (NAPA): *The Road Forward, A Vision for Net Zero Carbon Emissions for the Asphalt Paving Industry*, www.asphaltpavement.org/climate.
- Zweigle J, Bugsel B et al, University of Tubingen, *PFAS precursor characterization via UV/TiO_2 photocatalysis*, 2022.
- C&EN research; U.S. Geological Survey.
- Roskill Information Services, www.globalnewswire.com.
- An K, Azharuddin F, et al., The impact of climate solvent-based direct air capture systems, *Applied Energy*, November 2022.
- National Academies of Sciences, Engineering, and Medicine*: Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*; and Fasihi et al., *Technoeconomic assessment of CO_2 direct air capture plants,* The National Academies Press, 2019.
- Hassan M, Mohammad L, et al, *A Breakthrough in the Preparation of Highly-Sustainable Photocatalytic Warm Asphalt Mixtures*, Louisiana State University (LSU), National Science Foundation (NSF) Engineering Research and Innovation Conference, Atlanta, Georgia 2011.
- Heidelberg Cement Group, *Photocatalytic Communication Kit: The role of photocatalytic cement-based products as sustainable solutions*, www.heidelbergcement.com/en/sustainable-products.

The model then applied the aforementioned factors to current EPA estimates for vehicle exhaust emissions for standard passenger vehicles (90%) and medium-duty trucks (10%) to simulate an on-road estimate of available carbon and carbon equivalents relative to traffic flows using annual average daily traffic (AADT) with one exception related to non-exhaust emissions (NEE).[13]

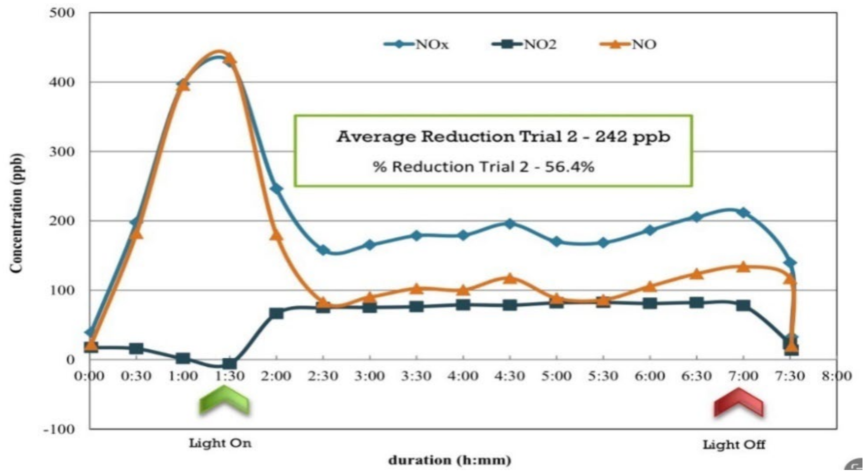
Select Research Laboratory & Field Data

[13] Emissions Analytics (UK), *Gaining traction, losing tread Pollution from tire wear now 1,850 times worse than exhaust emissions*, May 2022.

As noted, the literature has been extensive in the review of the past and current state of art using photocatalytic materials in asphalt pavement design. The photocatalytic mechanism, available testing standards, equipment and quantitative methods have been investigated comprehensively.

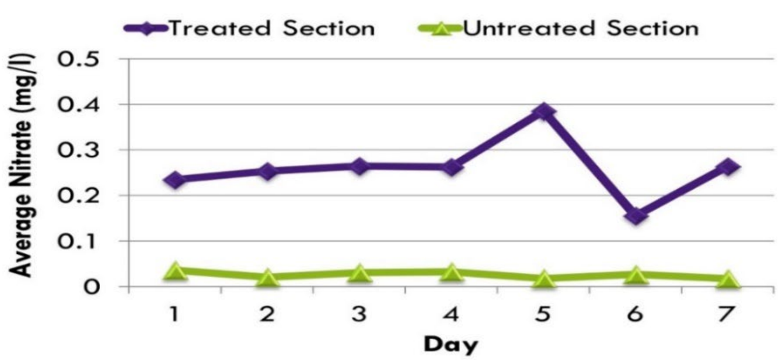
Here are a few research study conclusions:

In one of the earliest U.S. studies, Louisiana State University (LSU) performed a comprehensive analysis of pavements treated with TiO_2.[14] Two tests – reactive nitrogen reductions on pavement samples approached 60% in a photoreactor (Figure 1) and field pavement surface nitrate collection (Figure 2) showed a tenfold increase on treated surfaces, both proving strong photocatalytic activity.



Source: Louisiana State University (LSU), Department of Construction Management

Figure 1 – NOx, NO_2 and NO Reduction Efficiency



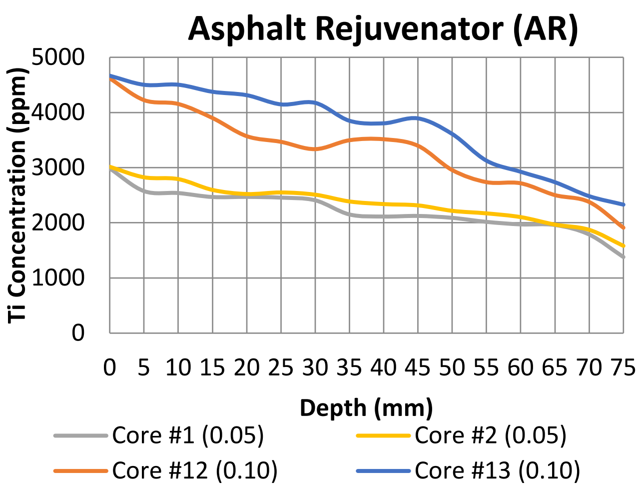
Source: Louisiana State University (LSU), Department of Construction Management

Figure 2 – In-Situ Nitrate Collection

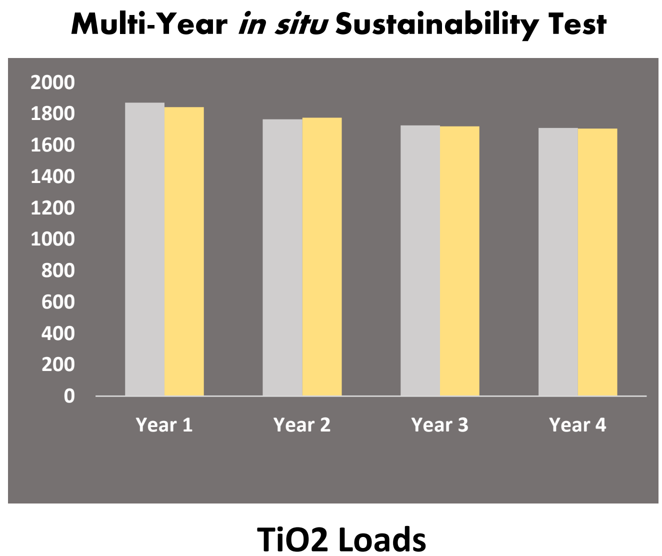
[14] Hassan M, Dylla H, et al, *Durability and Performance of Titanium Dioxide in Photocatalytic Pavements*, Louisiana State University, 2011.

Texas A&M University studied a spray-applied / penetrant approach that can be used with various pavement preservation products or techniques.

TiO_2 Penetration and Load: Treated pavements are consistently indicating strong photocatalytic grade TiO_2 delivery and durably through and below wearing-course depth (Figures 3 | 4).



Source: Texas A&M Transportation Institute (TTI)



Figures 3 | 4 – TiO_2 Penetration & Loading – Orlando International | Orlando

Nitrogen Oxide (NOx) Removal: Pavements field retrofit with TiO_2 are consistently showing 50% vehicular emission removal (Tables 2 | 3).

Compound	NO Reduction Efficiency (%)					
Application Rate	Control Sample	0.05 gsy	0.06 gsy	0.08 gsy	0.10 gsy	0.12 gsy
TiO2 Rejuvenator	NEGL	53%	57%	61%	53%	48%
TiO2 Penetrant ntroCME™	NEGL	48%	52%	55%	58%	53%

Source: Texas A&M Transportation Institute (TTI)

Table 2 –NO_x Reduction – Texas A&M Center for Infrastructure Renewal (CIR) [15]

Site	NO Reduction Efficiency (%)				
0.08 gsy > TiO_2	Rejuvenator	Rejuvenator	Penetrant	Penetrant	Litho1000Ti® Sample B
Orlando International	NEGL	45%	43%	53%	57%
Charlotte Co. (FL)	NEGL			42%	46%

Source: Texas A&M Transportation Institute (TTI)

Table 3 – NO_x Reduction – Orlando International Airport & Charlotte County [16]

UHI Mitigation: Asphalt pavements treated are consistently showing a 400% improvement in Solar Reflective Index (SRI) and qualify for U.S. Green Building Council LEED V4 Heat Island Reduction (HIR) and ISI ENV (Table 4).

Compound / Substrate	Solar Reflectance Index Values (SRI)					
Application Rate (a)	Control Sample	Control Sample	0.10 gsy	0.10 gsy	0.08 gsy	0.08 gsy
A.R.A.-1 Ti® / TiO2 Rejuvenator	9	8	40	39		
TiO2 Penetrant	24	24			38	38

Source: Texas A&M Transportation Institute (TTI)

Table 4 – Solar Reflectance – Orlando International Airport [17] [18]

Hydrophilic / Hydrophobic Pavements: TiO_2 is naturally hydrophilic, so treated pavements indicate better water desorption properties to create a more hydrophobic or quick drying pavement effect. Prevents water intrusion and surface ponding to reduce inclement weather-related traffic accidents (Table 5).

[15] Zollinger DG and Joshaghani A, *Laboratory Investigation of the Effect of TiO_2 Topical Treatments on Concrete and Asphalt Samples*, Texas A&M Transportation Institute, September 2018.

[16] Zollinger DG and Joshaghani A, *Laboratory Investigation of the Effect of TiO_2 Topical Treatments on Concrete and Asphalt Samples*, Texas A&M Transportation Institute, September 2018.

[17] Gopalakrishnan K, et al., *Climate Change, Energy, Sustainability, and Pavements*, Springer, 2014.

[18] Zollinger DG and Joshaghani A, *Solar Reflectance Analysis of TiO2 Penetrant Treatments on Concrete and Asphalt Samples*, Texas A&M Transportation Institute, August 2019.

Site	Water Contact Angle°				
A.R.A.-1 Ti®	Control Sample	TiO2 1 Visible Light	TiO2 1 UV Light	TiO2 2 Visible Light	TiO2 2 UV Light
FDOT Test	81°	82°	51°	81°	50°

Source: Texas A&M Transportation Institute (TTI)

Table 5 – Water Contact Angle – FDOT OGFC Test Bartow (FL) [19]

Microplastic Pollution (MPP) Removal: TiO_2 naturally decomposes microplastics e.g., tire-wear debris and brake-pad dust, which are evident from all vehicle types and exacerbated in EVs. Samples of the TiO_2 enhanced rejuvenator indicate near complete MPP decomposition in abbreviated time frames (Table 6).

	Microplastic Reduction Efficiency				
Sample	**Test (hours)**	**Pled (watts)**	**Diameter Beg**	**Diameter End**	**Volume Loss**
A	**2**	**110**	**100nm**	**37nm**	**94.8%**
B	**24**	**110**	**100nm**	**16nm**	**99.6%**

Source: Texas A&M Transportation Institute (TTI)

Table 6 –Microplastic Reduction – Texas A&M CIR [20] [21]

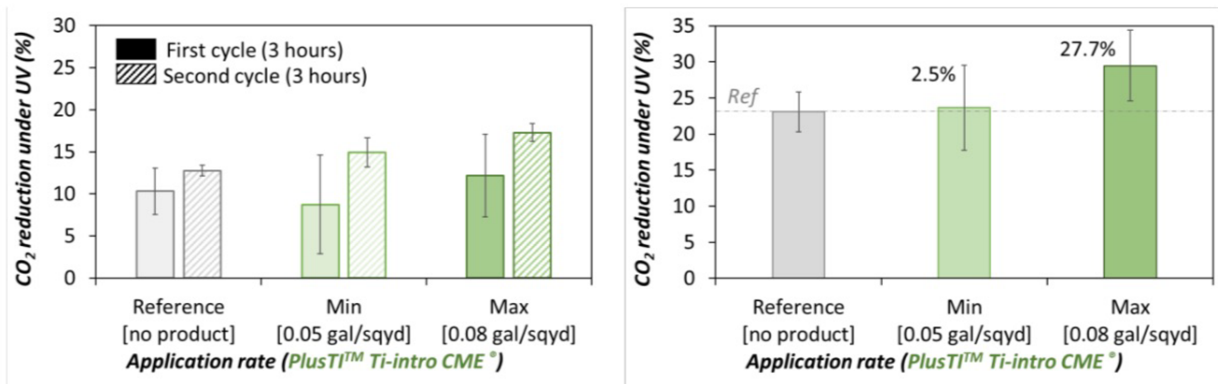
Carbon Dioxide removal using a TiO_2 penetrant: even with minimal product application, there was a 22% decrease in CO_2 concentration compared with samples without the product. More significantly, samples treated with the maximum product application rate achieved a remarkable 41% reduction in CO_2 concentration. This corresponds to a substantial enhancement in the pavement's CO_2 reduction capabilities when employing a TiO_2 additive (Figure 5).[22]

[19] Arainpour F and Farzaneh M, On Hydrophobic and Icephobic Properties of TiO_2-Doped Silicon Rubber Coatings, Department of Applied Sciences, Universite du Quebec, *International Journal of Theoretical and Applied Nanotechnology*, 2012.

[20] Nabi I and Bacha A, et al., Complete Photocatalytic Mineralization of Microplastic on TiO_2 Nanoparticle Film, iScience, July 24, 2020.

[21] Zollinger D and Philip J, Effect of TiO_2 Topical Treatments on Concrete and Asphalt for On-Road Microplastic Pollution Removal, Texas A&M Transportation Institute, August 2022.

[22] Velay Lizancos, M, Garcia Lopez-Arias, M, et al, *Carbon Dioxide Removal w/ Titanium Dioxide Pavement Additives Progress Report,* Purdue University, November 2023.



(a) **(b)**

Figure 9. *CDR under UV light results: (a) CO_2 reduction (%) per cycle; (b) total cumulative CO_2 reduction (%).*

Table 3 presents the tons of reduced CO_2 per km of road per year in comparison to the reference (no product added) under UV light exposure, calculated using Eq. 3.

Table 3. *Tons of reduced CO_2 per km of road per year due to the application of Ti-IntroCME on a concrete sample exposed to UV light.*

		CO_2 reduction (tons/km·year)
Penetrant	Minimum Rate	216.27
	Maximum Rate	1319.77

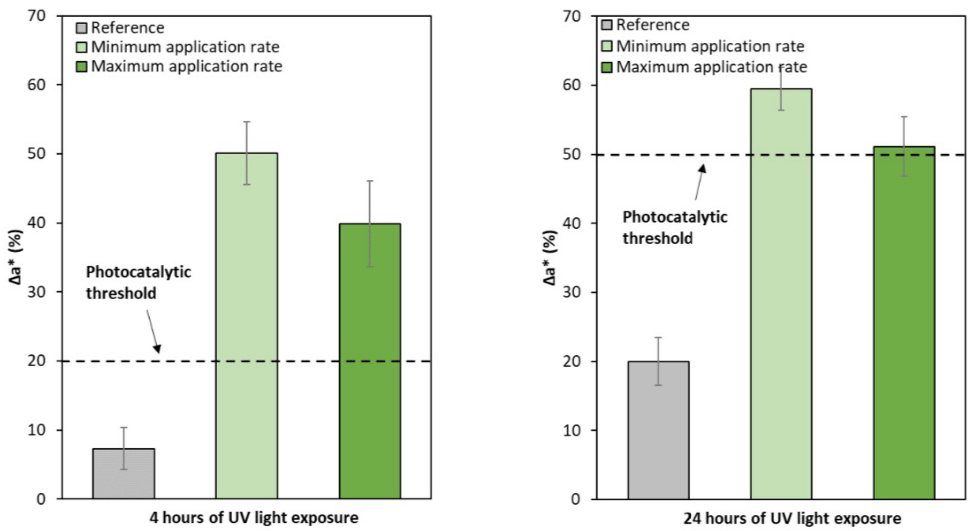
Source: Purdue University Lyles School of Civil Engineering

Figure 5 – CO_2 Reduction Efficiency w/ TiO_2 Pavement Additive [23]

Photocatalytic self-cleaning Test: result evidence that the application of a TiO2 pavement additive is beneficial to create significant photocatalytic activity and/or exhibit durable photocatalytic properties while compared to the reference group. The comparison further show that the application groups gain this advantage rapidly upon application (Figure 6).[24]

[23] Velay Lizancos, M, Garcia Lopez-Arias, M, et al, *Carbon Dioxide Removal w/ Titanium Dioxide Pavement Additives Progress Report,* Purdue University, November 2023.

[24] Velay Lizancos, M, Garcia Lopez-Arias, M, et al.



Source: Purdue University Lyles School of Civil Engineering

Figure 6 – Durable Photocatalytic Activity Test w/ TiO_2 Pavement Additive [25]

Mineralization CDR via Photocatalytic Pavement Retrofit

1Mt Annual (~345 Center Lane Kilometers) of TiO2 Enhanced Concrete

			Annual (Mt)	Cost ($mil)	Lifecycle (Mt)	Total Cost ($mil)
Scope 1, 2 (input)	Manufacturing & Installation of a Photocatalytic Penetrant ("cradle-to-pave" CO2e)(4)	CO2e	0.0 (one-time)	~$14.0 (one-time)	0.0* (two-times)	~$35.0*(2)
Scope 3 (external source)	Vehicle Emission 40,000 AADT(1)(3)	CO2	3.8		95	
Scope 3 (removal)	Photocatalytic Capture & Decomposition (PCD)	CO2	1.0		25	
	Net Carbon Dioxide Removal	CO2	1.0		25	
	Total Lifecycle Cost Per Tonne	CO2				<$5.00

*Possible second treatment of photocatalytic carrier.

Notes:
(1) AADT = Average Annual Daily Traffic
(2) 3% inflation
(3) 380 grams CO2 per vehicle per kilometer (EPA)
(4) There is no EOL needs for a photocatalytic pavement (no impact on asphalt recycling)

Figure 7 – Photocatalytic Pavement Upgrade Megaton Carbon Dioxide Removal Model [26]

[25] Velay Lizancos, M, Garcia Lopez-Arias, M, et al, *Carbon Dioxide Removal w/ Titanium Dioxide Pavement Additives Progress Report,* Purdue University, November 2023.

[26] Elon Musk Foundation | XPRIZE Foundation: $100 Million Prize Carbon Removal, Team "Photocatalytic Pavements", January 2024.

Business-as-Usual Baseline vs. Forecast

Using the East Central Florida Regional Planning Council PCAP, the Coalition expects to achieve nearly all of the Council's equivalent VMT reduction (just under the -12% gasoline and -6% diesel Council goal) upon successful completion of the CPRG Implementation Phase in 2030. This is illustrated in Figure 9 and equates to a net removal equal to 3,901,732,961 VMT using GHG reductions only (co-benefits were not included). With this accomplished the Region will be able to pursue other High Impact Priority Measures identified in the PCAP to achieve even greater equivalent reductions towards the 2050 goals.

East Central Florida Regional Priority Climate Action Plan

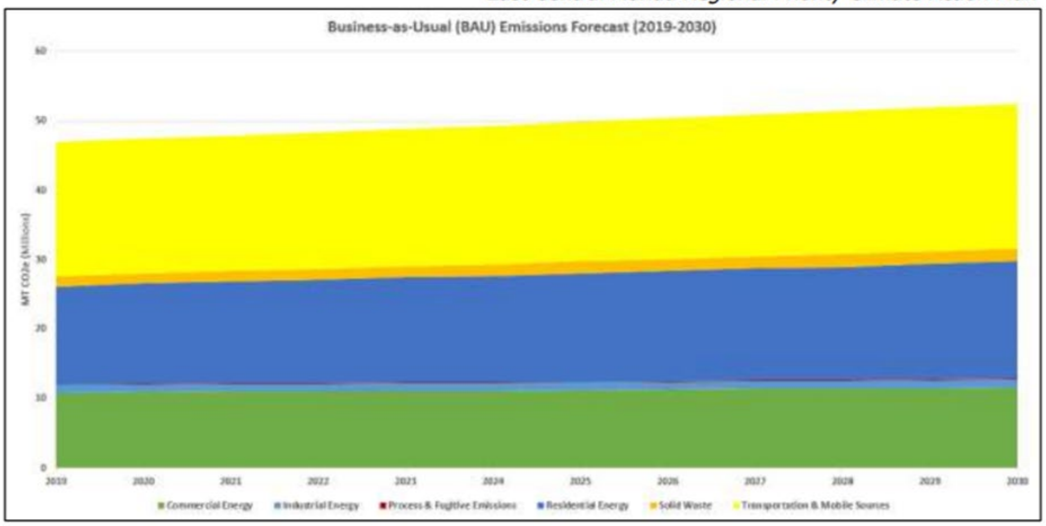


Figure 8 Business-as-usual (BAU) Forecast Case per ECFRPC PCAP page 32

3.2.2 High-Impact Action Modeling Results

The following chart compares Business-as-usual forecasted emissions to remaining emissions after the various high-impact actions and goals have been applied (see table 6).

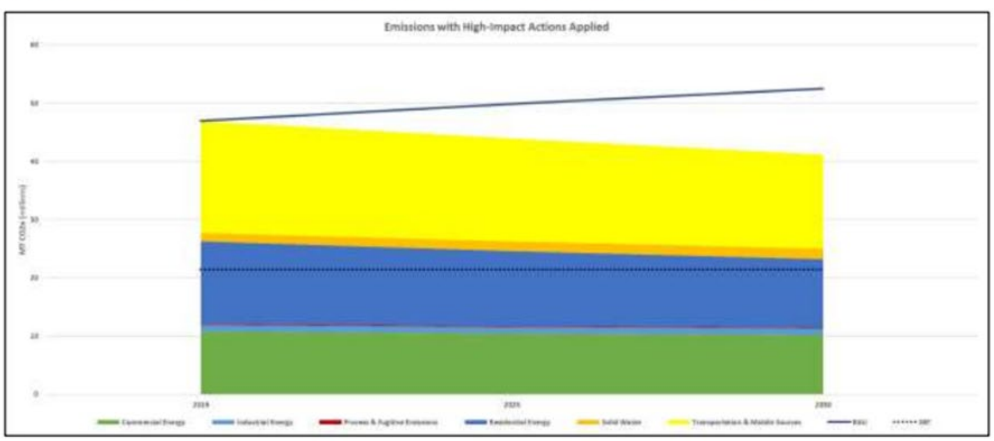


Figure 9 Business-as-usual forecasted emissions by 2030 after Coalition CPRG Implementation Phase page 32