Sustainable Aware Asset Management

Project: Asset Allocation with a Carbon Objective

Group S:

Ivan Khalin

Litian Zhang

Introduction and Methodology

This report provides an overview of various methods of portfolio construction and decarbonization, applied to the MSCI Emerging Market asset universe in the period of 2000 to 2021. We apply and evaluate multiple investment approaches, discuss their financial implications for investors, and evaluate their carbon impact. We begin by briefly discussing certain aspect of our methodology:

1. Data Collection

Our script considers data from multiple sources. From the 'DS_RI_T_USD_M.xlsx' file, we get the total return indexes and compute the simple returns for each asset on a monthly frequency. The data is transposed to allow easy indexing by date. The universe of assets is given by incorporating the data from the 'Static.xlsx'. Since we are only targeting the emerging markets category in our analysis, we create and apply a filter mask based on the ISIN codes of companies belonging to the EM category.

We then calculate asset returns. Obviously, the first observation (January 2000) is missing, so we manually backfill it with the observation from the following month. Additionally, the asset returns calculation invariantly returns infinite values when companies are newly listed or after being delisted from the market in the sample. We replace the infinite values and other missing observations with zero to tackle this issue.

Furthermore, there are several assets for which data is unavailable for the entire duration of our analysis. To account for this, we decided to exclude those assets that have zero returns for the entire last year of the in-sample data used for the portfolio construction. This is an important step in making sure that the optimization criterion provides reasonable asset allocations, because otherwise the portfolio will end up being comprised of unlisted, 'zero-variance' assets. Moreover, this filtering criterion does not cause a forward-looking bias, because the decision to exclude an asset is solely based on information in the sample.

2. Preventing Out-of-Sample Bias

We take special care to prevent our algorithm from accessing out-of-sample data throughout the optimization process. We decided to perform our optimization and portfolio evaluation iteratively to ensure that this is always the case. We achieve this by creating two predefined sets of indexes corresponding to in and out of sample data for any given year. For every iteration, the data is segmented into two datasets: one containing the monthly returns available prior to the portfolio allocation and the other containing the monthly returns for the year in which the allocation is to be implemented and evaluated.

3. Portfolio Construction

The portfolio construction procedure must be performed by means of numerical optimization. This is the case because covariance matrix of asset returns is not full-rank and non-invertible, due to the large sample size. Therefore, we cannot simply evaluate the minimum variance equation. Hence, our portfolio construction relies on the CVXPY module, specialized in tackling convex optimization problems. We define an objective function and a set of constraints specific to each scenario. The optimizer requires initial values for weights as an input, which we set to 1/N, where N is the number of assets under consideration for that period. The optimization is then performed one period at a time as described in the section above. Subsequently, we calculate the relevant portfolio metrics and store them for later analysis.

4. Performance Evaluation Metrics

As alluded to previously, we evaluate the monthly performance metrics of our portfolio and report the mean annualized returns, volatility, and Sharpe Ratio. The risk-free rate of interest used in calculating the Sharpe ratio is the monthly US T-bill corresponding to the month in which the ratio is computed, assuming the perspective of a US-based investor.

It is essential to account for the fact that monthly portfolio returns are affected by the changing values of the underlying assets. Since we only rebalance out portfolios annually, the asset allocation gradually shifts away from the prescribed optimum. Therefore, portfolio returns must account for this dynamic by updating the weights. The portfolio evaluation procedure tracks the dynamic of asset returns each month, ensuring our asset allocation actively adjusts for price fluctuations. The portfolio performance is evaluated based on these dynamically adjusted weights at the end of each investment year.

With that in mind, we now outline the **NUMBER** types of portfolio construction criteria that will be used in the subsequent sections of our analysis:

1. The first portfolio $P^{(mv)}$ (Section 1) is a long only minimum variance portfolio:

$$\min_{\{\alpha_Y\}} \sigma_{p,Y}^2 = \alpha_Y' \Sigma_{Y+1} \alpha_Y$$
$$s.t. \quad \begin{aligned} &\alpha_Y' e = 1 \\ &a_{i,Y} \geq 0 \ \forall i \end{aligned}$$

2. The second portfolio $P^{(mv(0.5))}$ (Section 2) is the same minimum variance portfolio with an additional carbon footprint constraint targeting 50% of emissions of $P^{(mv)}$.

$$\min_{\{\alpha_Y\}} \sigma_{p,Y}^2 = \alpha_Y' \Sigma_{Y+1} \alpha_Y$$
$$s.t. \quad \begin{aligned} &CF_Y^{(p)} \leq 0.5 \times CF_Y^{\left(P_{oos}^{(mv)}\right)} \\ &a_{i,Y} \geq 0 \ \forall i \end{aligned}$$

3. The third portfolio $P^{(vw(0.5))}$ (Section 3) minimizes the squared tracking error with the reference taken as the value weighted portfolio $P^{(vw)}$ with an additional carbon footprint constraint targeting 50% of emissions of $P^{(vw)}$.

$$\min_{\{\alpha_Y\}} \left(TE_{p,Y}\right)^2 = \left(\alpha_Y - \alpha_Y^{(vw)}\right)' \Sigma_{Y+1} \left(\alpha_Y - \alpha_Y^{(vw)}\right)$$
$$s.t. \quad \begin{aligned} &CF_Y^{(p)} \leq 0.5 \times CF_Y^{\left(P_{oos}^{(vw)}\right)} \\ &a_{i,Y} \geq 0 \ \forall i \end{aligned}$$

4. The fourth portfolio $P^{(vw(NZ))}$ (Section 3) also minimizes the squared tracking error with the reference taken as the value weighted portfolio $P^{(vw)}$ with an additional carbon footprint constraint targeting an ever-decreasing fraction of emissions of $P^{(vw)}$.

$$\min_{\{\alpha_Y\}} \left(TE_{p,Y}\right)^2 = \left(\alpha_Y - \alpha_Y^{(vw)}\right)' \Sigma_{Y+1} \left(\alpha_Y - \alpha_Y^{(vw)}\right)$$
$$s.t. \quad \begin{aligned} &CF_Y^{(p)} \leq (1-\theta)^{Y-Y_0+1} \times CF_{Y_0}^{\left(P_{oos}^{(vw)}\right)} \\ &a_{i,Y} \geq 0 \ \forall i \end{aligned}$$

PART 1 – Standard Asset Allocation

1.1 & 1.2: Minimum Variance Portfolio (MV) & Value-Weighted Portfolio (VW)

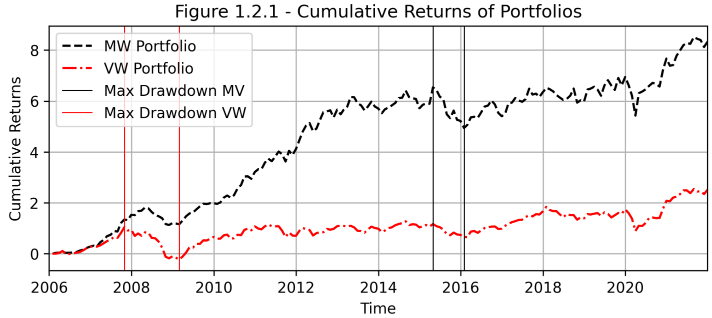
Starting on a strong foot, the minimum variance portfolio performed remarkably well in the emerging markets asset universe. The exceedingly positive nature of its performance is especially evident when compared to the value-weighted portfolio, which performed rather poorly. The two portfolios presented the following out-of-sample performance metrics:

Table 1.1.2: MV vs VW		
Metric	**MV** ($P_{oos}^{(mv)}$)	**VW** ($P_{oos}^{(vw)}$)
Annualized Mean Return	0.1614	0.0958
Annualized Volatility	0.1415	0.2074
Sharpe Ratio	1.0574	0.4013
Minimum Return	-0.1085	-0.2662
Maximum Return	0.1717	0.1853
Maximum Drawdown	1.5973	1.2697
Period of Maximum Drawdown	2015/04 – 2016/01	2007/10 – 2009/02

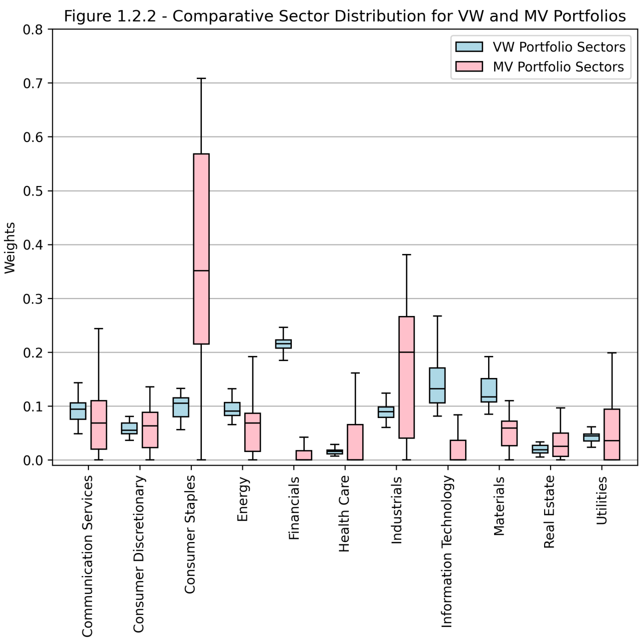
The minimum-variance portfolio exceeded the benchmark in all, but the maximum observed annualized monthly return. The average annualized return was higher, while the annualized volatility was lower, leading to a Sharpe ratio of 1.06 for the minimum variance portfolio, more than two and a half times higher than the benchmark's 0.4 Sharpe ratio. Initially, we were taken aback by these findings. Needless to say, we have performed the due diligence in verifying these results, with additional information available in the **Appendix – Verification** section.

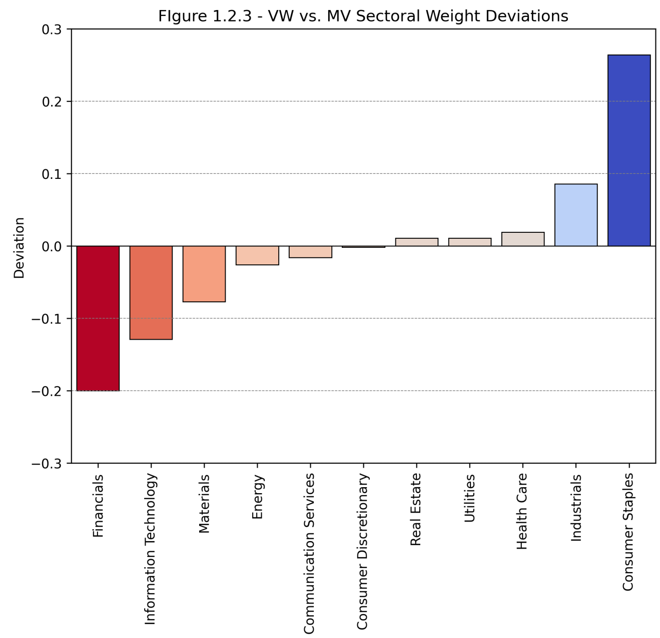
In the absence of evidence of incorrect implementation, let us turn our attention to alternative explanations of this overperformance. We believe that these differences can be explained by the difference in the nature of the value weighted and minimum variance strategies. The VW portfolio systematically overweighs a few large-cap stocks and underweights the assets that have a lower market cap. The assets with a high market capitalization may not deliver sufficiently high growth, unlike the low-cap assets. This shortcoming of the VW portfolio becomes increasingly apparent in the context of emerging markets, which are characterized by rapid economic growth. The VW fails to harvest this upward market momentum and becomes pinned to relatively low performance due to its large weights in value, rather than in growth stocks. The MV portfolio on the other hand, does not suffer from this selection problem, because it chooses assets based solely on their volatility.

Figure 1.2.1 - Cumulative Returns of Portfolios



Interestingly, the maximum drawdown for the two portfolios did not occur in the same time period, with the value-weighted portfolio reaching its lowest value in February 2009, while the minimum variance portfolio bottomed out in March 2020. An alternative explanation that could shed light on the differences in drawdown timing and the dominant performance of the MV portfolio are the differences in sectoral allocations between the two strategies, which are depicted in Figures 1.2.2 and 1.2.3. For instance, information technology and financials are the two categories with the highest overall inclusion in the value-weighted portfolio throughout the years, whereas these two categories are amongst the three least included in the minimum variance portfolio. Additionally, the minimum variance portfolio tends to give preferential treatment to the consumer staples sector, with the median allocation approaching 40% of the total makeup of the portfolio. More generally, the value-weighted portfolio weights are less dispersed, with the Q4-Q0 range typically under 10%, while the minimum variance portfolio range is, on average, closer to 20%.





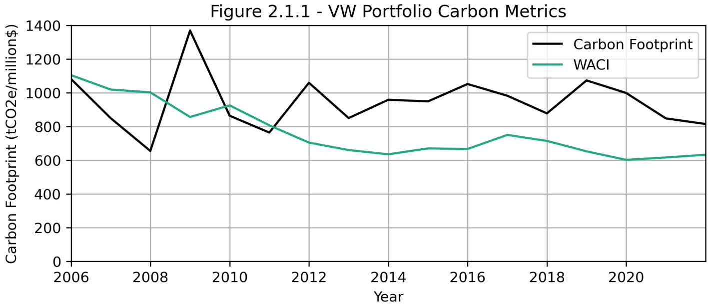
Finally, another stark difference in the performance of the two strategies was their respective performance in times of crises and market turmoil. First, when the market was confronted with the global financial crisis between mid-2007 and early 2009, the value-weighted portfolio reacted more aggressively because 21.46% and 19.76% of the portfolio weights were allocated to financial industries in January 2008 and 2009 respectively. Conversely, in the same time period, the minimum variance portfolio allocated 62.21% and 62.61% to the consumer staples sector. These industries should have not suffered as big of a loss due to the financial crisis as the financial industry did.

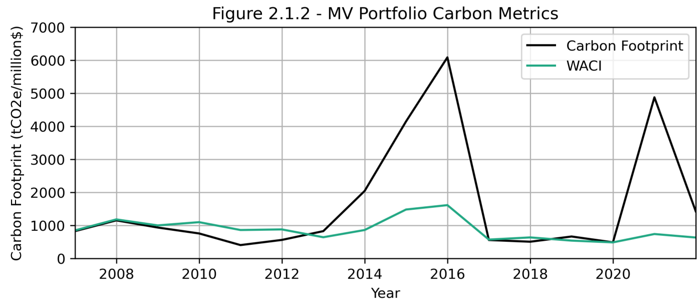
Second, looking at the period between 2015 May and 2016 February, the tables have turned and the differences in sectoral allocation now work in favor of the VW portfolio. In the value-weighted portfolio, 35.67% of the portfolio weights are concentrated in the Information Technology and Financial sectors, whereas in the minimum-variance portfolio, 49.32% of the portfolio weights are invested in the Consumer Staples, Industrials, and Communication Service sectors and 0% was invested in Financial sectors. At this time, multiple events transpired that could have had an adverse effect on the performance of the three major sectors in the MV portfolio, for instance, the Chinese stock market crash and the commodity price crash. Since the MV portfolio was not invested in the ‘financial’ sectors, the impact of these events was not diversified away from the invested sectors and weighed heavily on MV’s performance.

PART 2 – Asset Allocation with a Carbon Emissions Reduction

2.1 – Benchmark

We start by comparing the carbon metrics of the VW and MV portfolios. We can see from Figure 2.1.1 that the carbon footprint of our value weighted portfolio decreases over time. Although the VW portfolio performed rather poorly as mentioned in Part 1, the overall trend was still positive. Therefore, the reduction of the carbon footprint suggests that there was an organic reduction in the emissions of the companies that comprise this portfolio. The WACI displays a similar trend, but with significantly less variation. Interestingly, although in 2006 the carbon footprint and WACI oscillate around a similar level, from 2010 onwards WACI is systematically lower than the carbon footprint until the end of the sample.





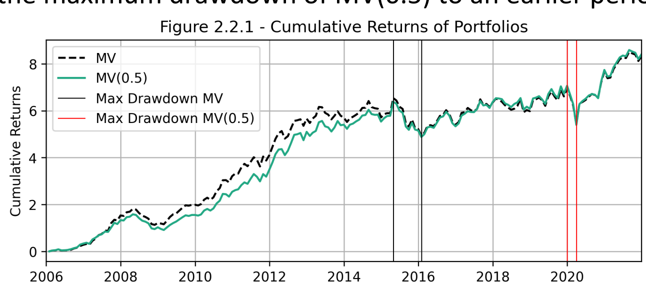
For the minimum variance portfolio, the carbon footprint of is quite erratic, with periods of relatively low emissions followed by large spikes, as shown in Figure 2.1.2. Although initially the carbon footprint decreased substantially, in the years following 2012 it has increased over 10 times since its minimum in 2011, before falling back to the 2012 levels in 2017. The spike in 2020 further makes it difficult to extract a trend for the general movement of the carbon footprint. Just as with the VW portfolio, the WACI for the MV portfolio was significantly more stable, although some sense of its variation is lost in comparison to the massive spikes in carbon footprint. The overall trend for WACI appears to be a reduction.

2.2 - Standard Allocation - 50% reduction (MV vs MV(0.5))

The performance of the decarbonized portfolio MV(0.5) is very similar to that of the standard minimum variance portfolio, with the only notable change being the period of the maximum drawdown. MV(0.5) performed slightly better in terms of mean return, volatility, Sharpe Ratio, and minimum return, and slightly worse in terms of the maximum return and drawdown. The out-of-sample performance metrics for MV(0.5) are shown below in Table 2.1.2:

Table 2.1.2: MV vs MV(0.5)		
Metric	**MV**	**MV(0.5)**
Annualized Mean Return	0.1614	0.1622
Annualized Volatility	0.1415	0.1380
Sharpe Ratio	1.0574	1.0893
Minimum Return	-0.1085	-0.1024
Maximum Return	0.1717	0.1366
Maximum Drawdown	1.5973	1.6815
Period of Maximum Drawdown	2015/04 – 2016/01	2019/12 – 2020/03

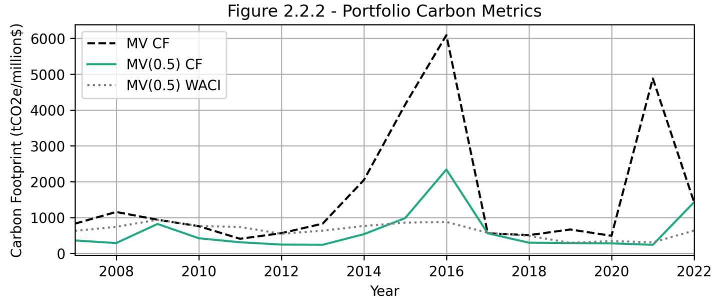
The cumulative performance of MV(0.5) closely tracks that of MV, with a trend of slight underperformance that turns to a slight overperformance in 2018. These variations do not represent a significant departure and are insufficient to conclude that one portfolio has a systematic tendency to outperform the other. The difference in maximum drawdown dates is due to the fact that the drawdown amounts for the 2015-2016 and 2019-2020 periods were very close to begin with for the MV portfolio. Consequently, a slight underperformance in 2015-2016 and a slight overperformance in 2019-2020 relative to the MV, pushed the maximum drawdown of MV(0.5) to an earlier period.



The carbon footprint of MV(0.5) attempts to always stay below the carbon footprint of MV. At times, this does not happen, because the carbon footprint of the two portfolios is measured ex-post, whereas the optimization procedure uses last known carbon footprint data. Consequently, there exist two scenarios in which the ex-post carbon footprint of the decarbonized portfolio MV(0.5) will not be below the ex-post carbon footprint of MV. The first scenario occurs when the selected companies end up polluting more in the year following their selection, than they did in the year prior. Since the carbon footprint constraint is determined based on the last known emissions data, the MV(0.5) portfolio can only target the ex-ante carbon footprint.

The second scenario occurs when the MV portfolio spontaneously and significantly reduces its carbon footprint, yet, since the MV(0.5) portfolio targeted a 50% reduction relative to the last years carbon footprint, its ex-post emissions no longer satisfy that target during the year. Indeed, a combination of these scenarios is possible and occasional failures to stay below the 50% target are inevitable. Nevertheless, the MV(0.5) portfolio succeeded in always having a lower carbon footprint than MV, with spikes and drops in emissions that track the MV portfolio with a one-year lag.

Figure 2.2.2 - Portfolio Carbon Metrics



In implementing a decarbonization strategy, we are interested in keeping track of how our sectoral exposures change as a result of the constrained asset selection. Compared to the differences in sectoral allocation between the VW and MV portfolios, the differences in sectoral allocations between the MV and MV(0.5) portfolios are minute, as evidenced by Figure 2.2.3 Unlike in the Figure 1.2.3. The Figure 2.2.4 shows that the sectoral differences are an order of magnitude smaller, with the energy, materials and industrials sectors getting traded for financials, real, estate, health care and communication services. Such a small discrepancy in sector allocations is initially somewhat surprising, given that MV(0.5) targets a carbon footprint reduction of 50%. One possible explanation for these low sectoral deviations is that, due to extreme asymmetry in the distribution of carbon emissions, decarbonization can be achieved by selectively divesting from a few highly polluting companies, rather than a given sector as a whole, thereby conserving the general sectoral makeup of the MV portfolio.

Comparative Sector Distribution for MV vs. MV(0.5)

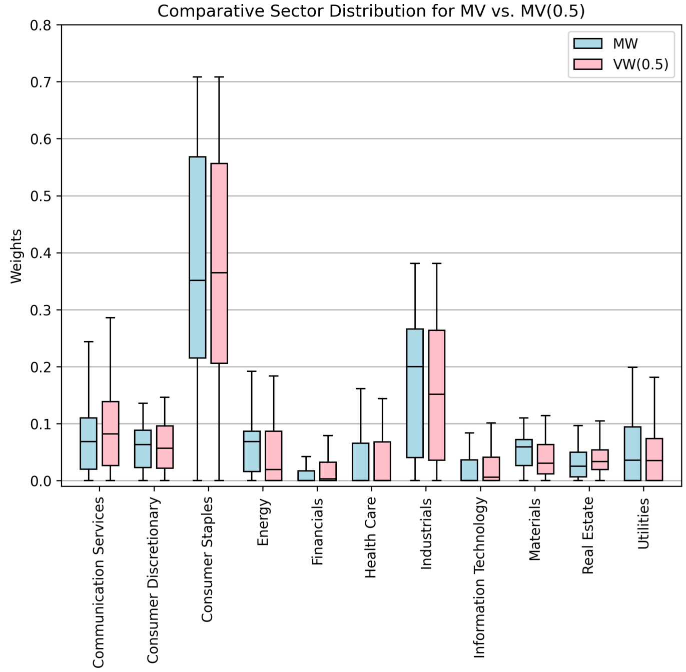
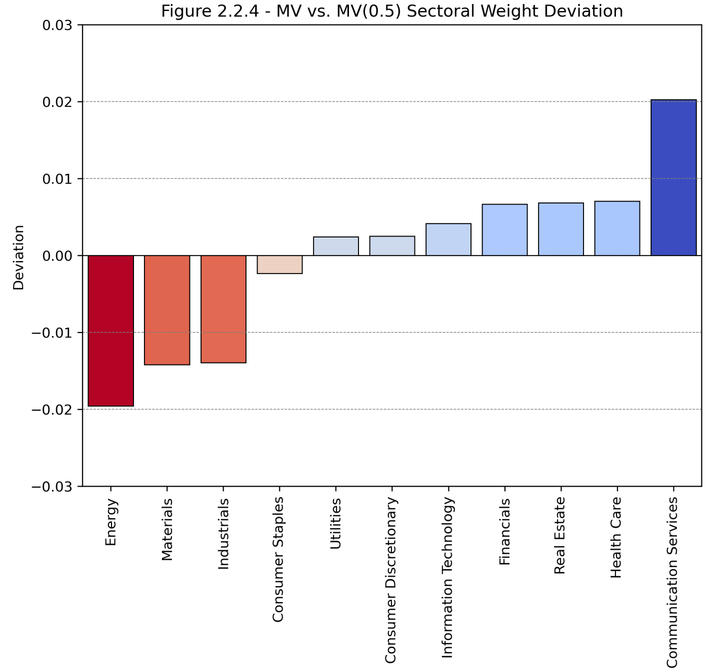


Figure 2.2.4 - MV vs. MV(0.5) Sectoral Weight Deviation



2.3 - Benchmark Portfolio - 50% reduction (VW vs VW(0.5))

The value-weighted portfolio with 50% reduction in carbon footprint is found by minimizing the squared tracking error relative to the value weighted portfolio, subject to the constraint of a 50% carbon footprint reduction. The performance of VW(0.5) is marked by a subtle yet systematic overperformance of the VW benchmark, as well as the improvement of all other aspects except the minimum out-of-sample return and the maximum drawdown. These amounted to the following performance metrics in Table 2.3.1:

Table 2.3.1: VW vs VW(0.5)		
Metric	**VW**	**VW(0.5)**
Annualized Mean Return	0.0958	0.1214
Annualized Volatility	0.2074	0.2071
Sharpe Ratio	0.4013	0.5308
Minimum Return	-0.2662	-0.2627
Maximum return	0.1853	0.1878
Maximum Drawdown	1.2697	1.3631
Period of Maximum Drawdown	2007/10 – 2009/02	

Contrary to the comparison of the MV and MV(0.5) portfolios, there appears to be a trend of systematic overperformance when looking at the cumulative returns in Figure 2.3.1. Although specific sources of this excess performance likely stem from the sectoral changes discussed below, it can be said that when the carbon footprint constraint is binding, the optimization criterion will shift towards the allocations similar to the minimum variance portfolio. This is the case because the asset weight deviations are scaled by the variance of assets for which those deviations are incurred. Therefore, when the carbon constraint is binding, the optimization procedure will first forgo the assets with the lowest variance, since their low variance will 'reduce the penalty' for deviating from the benchmark VW. Given this insight and recalling the outstanding performance of the MV portfolio, it should not be surprising that the VW(0.5) portfolio outperformed VW.

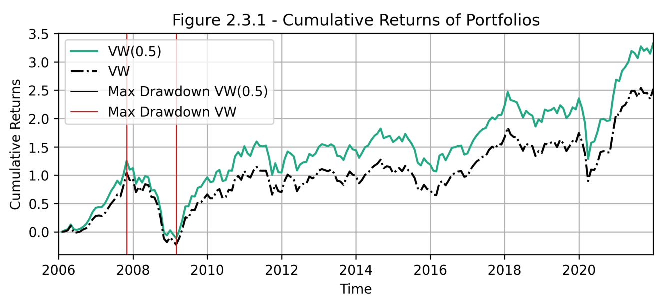
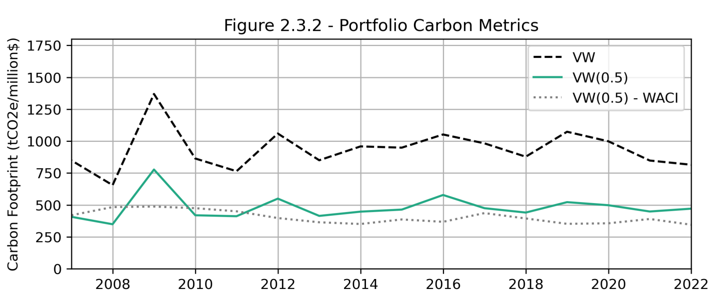


Figure 2.3.2 shows that the VW(0.5) portfolio is significantly better at staying at or below the 50% of the carbon footprint of its reference portfolio than the MV(0.5) portfolio was. Furthermore, we do not observe the same one-year lag in carbon footprint levels as we did with the MV(0.5). The reasons for this are twofold. First, the weights of the benchmark reference portfolio VW are significantly more stable than minimum variance weights and evolve gradually over time. Therefore, there were less sudden jumps in the carbon footprint, making the situation where the VW carbon footprint decreases dramatically YoY (and makes VW(0.5) exceed the target carbon footprint) less probable. Second, the VW(0.5) portfolio attempts to stay as close as possible to the composition of VW, thereby reducing the likelihood of discrepancies in carbon footprint movements. Notice that these two reasons act opposingly to the two factors, described in section 2.2, that caused the MV(0.5) portfolio to fail at staying below its carbon footprint target.



The sectoral weights deviations in Figures 2.3.3 and 2.3.4 for the VW(0.5) portfolio are surprising for two reasons. The first surprise lies in that these sectoral deviations are on average twice as big as the deviations between the MV and MV(0.5) portfolios, which is counterintuitive given that VW(0.5) is specifically constructed to minimize the tracking error. A potential explanation for this could be that the carbon footprint reduction constraint is significantly more binding in the case of the VW(0.5) portfolio, which is possible given the dramatic emissions spikes of the MV portfolio in Figure 2.1.2. Therefore, VW(0.5) had to make larger weight shifts to satisfy the targeted carbon footprint.

The second surprise is that the decarbonized portfolio VW(0.5) reduced its average exposure to the IT sector, all the while increasing its exposure to industrials. This could be explained by the presence of highly polluting firms in the IT category, for instance firms operating large server infrastructure could have been excluded. The exclusion of such firms would constitute a large sectoral shift if these companies had high market capitalization, and therefore, significant weight in the benchmark VW portfolio. Additionally, recall the above discussion of the optimization procedure's tendency to exclude assets with the lowest variance when the carbon constraint is binding. From this point of view, it would not be surprising for the excluded assets to come from sectors with historically low volatility. Although this explanation is not likely to fully justify the large deviations in the IT sector that has been historically volatile, it is possible that there were periods in the sample when the 5-year rolling window captured periods of low volatility.

Figure 2.3.3. - Comparative Sector Distribution for VW vs. VW(0.5)

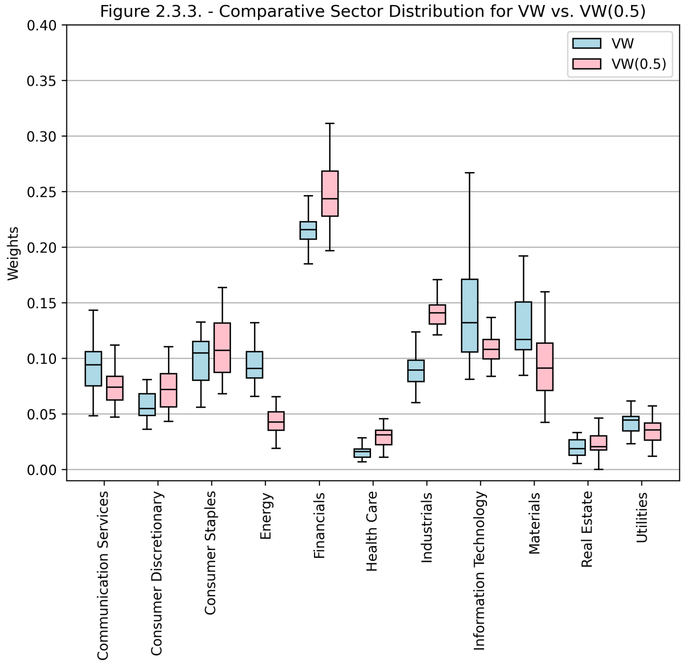
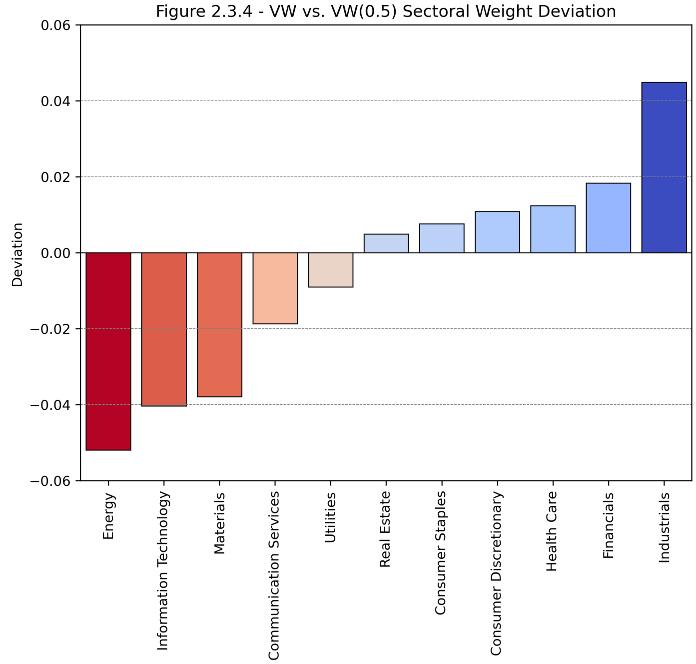


Figure 2.3.4 - VW vs. VW(0.5) Sectoral Weight Deviation



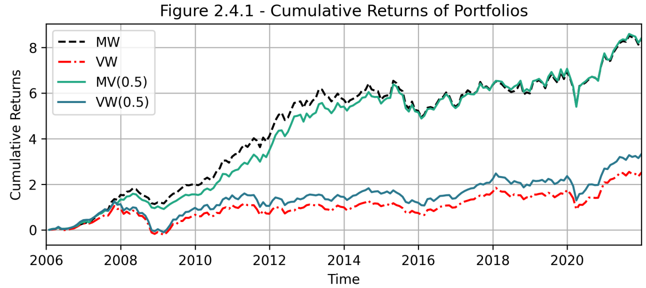
2.4 - Tradeoffs in 2.2 and 2.3

The two decarbonization strategies suggest that reducing the carbon footprint of a portfolio does not result in worsened financial performance. Table 2.4.1 summarizes all the numeric performance metrics discussed in Section 2:

Table 2.4.1: MV vs MV(0.5) & VW vs VW(0.5)				
Metric	**MV**	**MV(0.5)**	**VW**	**VW(0.5)**
Annualized Mean Return	0.1614	0.1622	0.0958	0.1214
Annualized Volatility	0.1415	0.1380	0.2074	0.2071
Sharpe Ratio	1.0574	1.0893	0.4013	0.5308
Minimum Return	-0.1085	-0.1204	-0.2662	-0.2627
Maximum return	0.1717	0.1366	0.1853	0.1878
Maximum Drawdown	1.5973	1.6815	1.2697	1.3631
Period of Maximum Drawdown	2015/04 – 2016/01	2019/12 – 2020/3	2007/10 – 2009/02	

The cumulative performance in Figure 2.4.1 shows that whichever decarbonization strategy we are implementing, MV(0.5) or VW(0.5), the cumulative performance closely tracks that of the reference portfolios MV and VW. Therefore, in terms of financial performance, the more relevant question is which investment strategy to decarbonize, rather than whether to decarbonize or not.

Figure 2.4.1 - Cumulative Returns of Portfolios



In terms of reduced emission, the least polluting of the 4 strategies was the decarbonized value weighted portfolio VW(0.5). Although it surpassed the carbon footprint of the MV(0.5) portfolio in some periods, the spikes in emission of the MV(0.5) portfolio were large enough to compensate for those exceedances. The Figure 2.4.3 leads to a similar conclusion when the emissions are tracked in terms of WACI.

Figure 2.4.2 - Portfolio Carbon Footprint

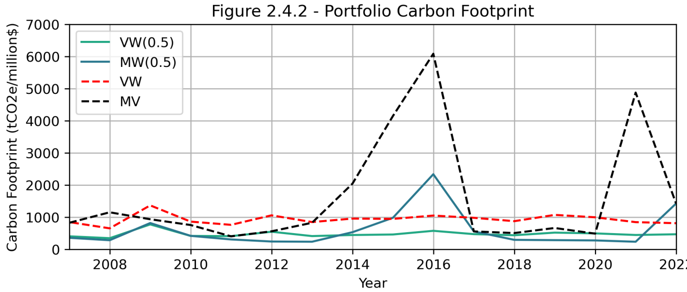


Figure 2.4.3 - Portfolio WACI

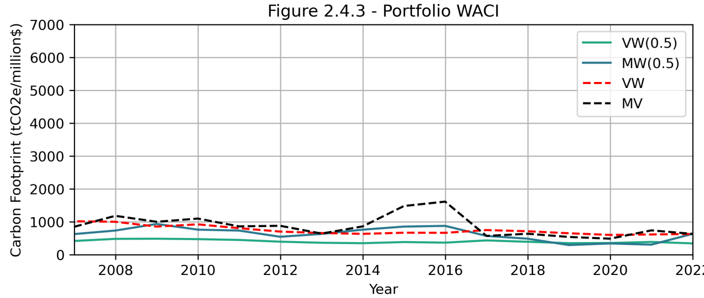


Figure 2.4.4 - Comparative Sector Distirbution WV, WV(0.5), MV, MV(0.5)

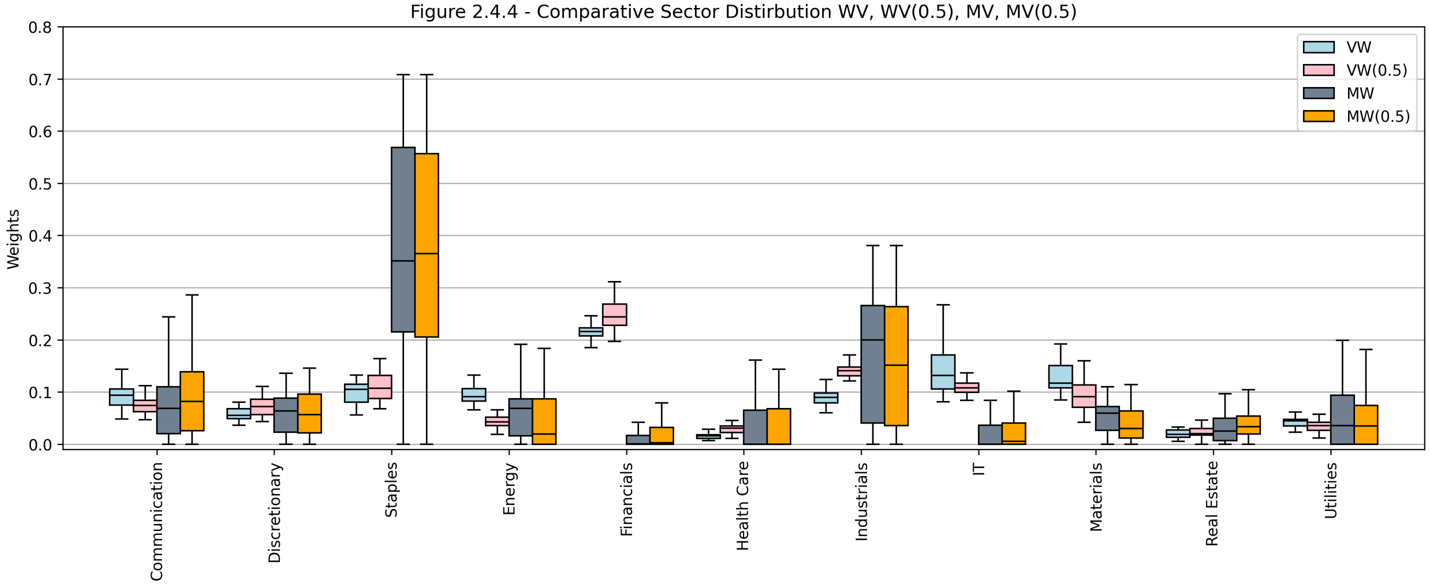
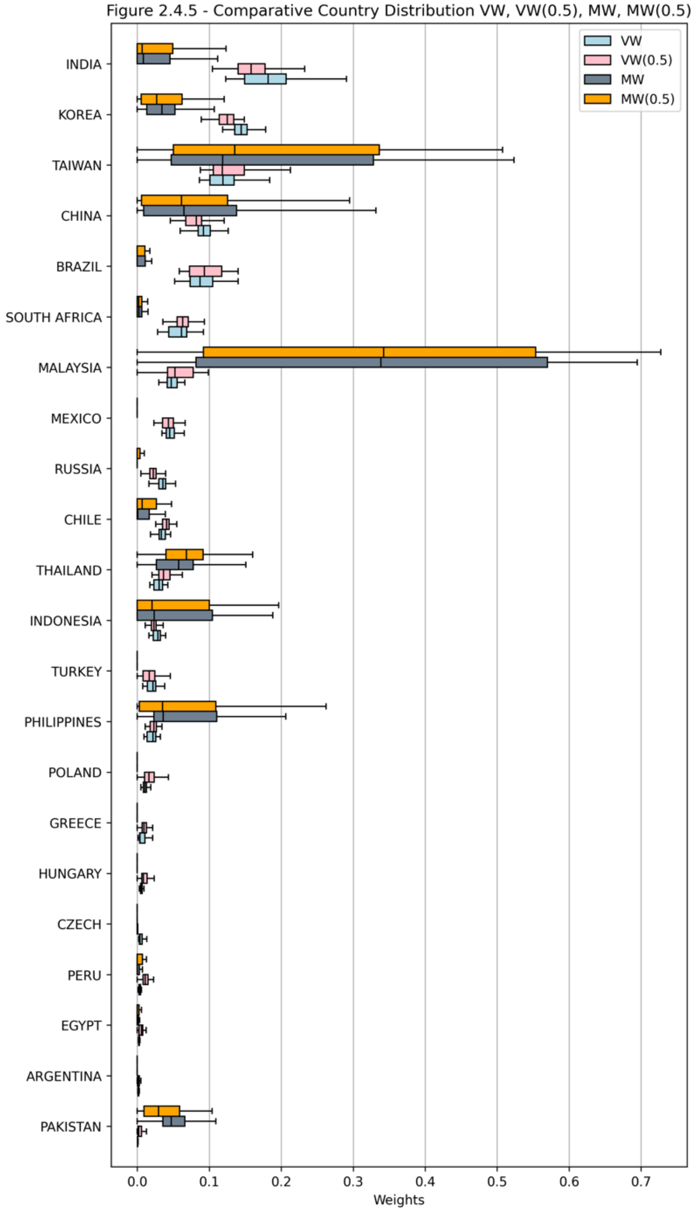


Figure 2.4.5 - Comparative Country Distribution VW, VW(0.5), MW, MW(0.5)



Perhaps the most significant differences between reference strategies and their decarbonized counterparts, stem from the changes in sectoral and regional exposures. As seen in the above discussions for the VW(0.5) and MV(0.5) portfolios, the sectoral changes when implementing a decarbonization strategy are not significant. Figures 2.4.4 and 2.4.5 convey the overall changes in sectoral and regional allocations respectively. Both figures lead us to the same conclusion that the cumulative performance suggested – the choice of the appropriate investment strategy is not about whether decarbonization should be implemented or not, but more about which strategy should be chosen as the reference.

This conclusion is supported by the fact that sectoral and regional exposures barely differ between the pairs of reference and the decarbonized strategies (VW vs. VW(0.5), MV vs. MV(0.5)), yet differ significantly between the types of strategy – value weighted or minimum variance.

Of the two decarbonized portfolios VW(0.5) and MV(0.5), the exposures of the value weighted portfolio were subject to more significant change. As previously mentioned, this was likely the result of the more binding carbon footprint constraint, which led to bigger deviations from the reference portfolio VW. This observation reveals a general insight into decarbonized portfolio construction: that is – the less polluting the reference portfolio to be decarbonized, the more investors should expect their sectoral and regional exposures to change because of the binding carbon constraint. As per the performance, there does not appear to be a surefire way of anticipating how it will be affected by imposing an emissions constraint, all we can conclude is that the decarbonization does not severely worsen the cumulative return of our portfolio, thanks to the effectiveness of excluding highly polluting firms in reducing the carbon footprint of a portfolio.

PART 3 – Allocation with a Net Zero Objective

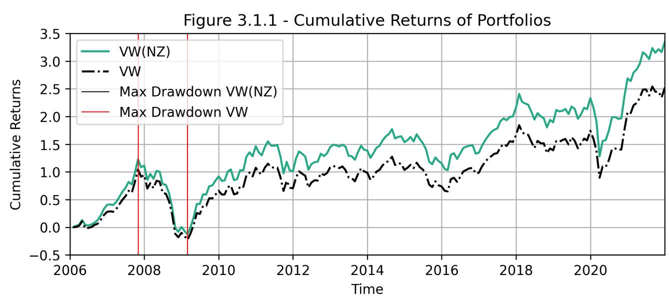
3.1 - Benchmark Portfolio - Net Zero Target

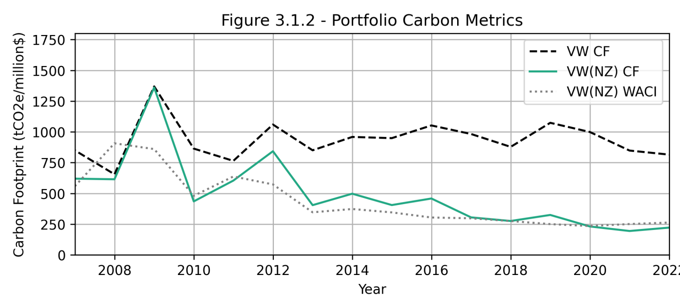
Comparing summary statistics between the value-weighted portfolio (VW) and the value-weighted portfolio with net zero objectives VW(NZ) in Table 3.1.1. We can see that net zero strategy delivers overall better performance than the VW portfolio. The annualized return is higher for the net zero strategy, but the volatility remains the same for both approaches, resulting in Sharpe ratio being 0.1 higher. The minimum and maximum returns are almost identical for both strategies. However, the VW(NZ) portfolio suffers more loss than the VW portfolio during the global financial crisis in 2008.

From the Figure 3.1.1, we can see that the tracking error is very small in the beginning of our sample but gets wider with time. A similar trend can also be detected in Figure 3.1.2. If we draw a hypothetical straight line representing the level of carbon footprint in 2006, the VW portfolio remains at approximately the same level in 2022, suggesting that the emerging market industries are not doing much in the way of decarbonizing. Conversely, our VW(NZ) portfolio succeeds in adhering to the 'net zero' objectives with a clear downward trend in terms of carbon footprint. Therefore, achieving the more restrictive net zero objective is naturally coupled with incurring a larger tracking error, it is thus of no surprise to see the difference in returns enlarge throughout the years.

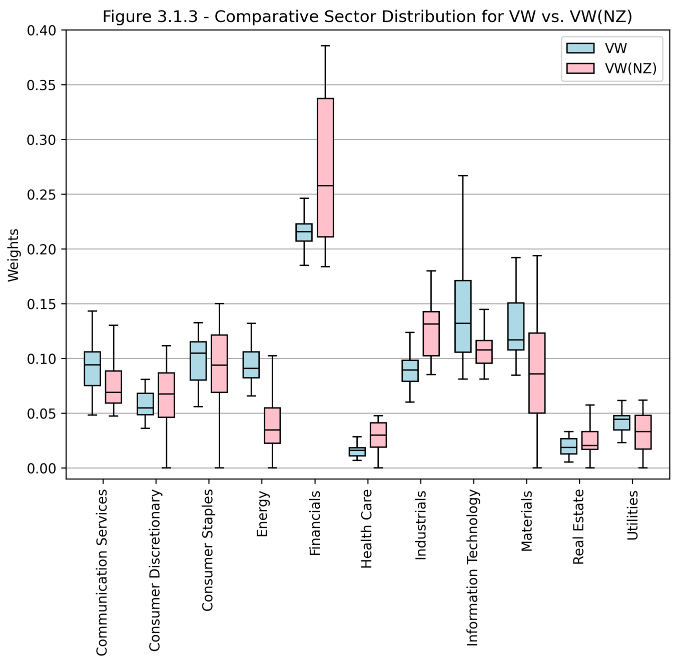
Table 3.1.1: VW vs VW (NZ)

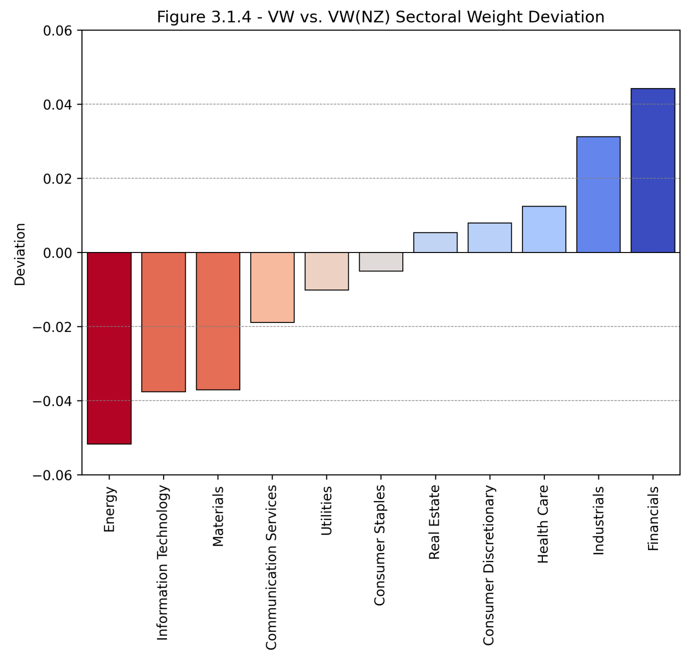
Metric	**VW**	**VW(NZ)**
Annualized Mean Return	0.0958	0.1216
Annualized Volatility	0.2074	0.2073
Sharpe Ratio	0.4013	0.5314
Minimum Return	-0.2662	-0.2618
Maximum return	0.1853	0.1882
Maximum Drawdown	1.2697	1.3545
Period of Maximum Drawdown	2007/10/31 – 2009/02/28	





The bars in Figure 3.1.4 are computed based on the average monthly differences in the weights across two portfolios. Although the sectoral weights reallocation is about twice as big as with the VW(0.5) portfolio, they are still quite moderate, since our objective is to minimize the tracking error. Looking at the impact from net zero objective to the sector weights, the 'usual suspects' such as energy and material sectors are divested from the VW portfolio and reinvested in less polluting sectors such as financials, real estate, and health care sectors. Although, once again, we have the surprising increase in allocations to the industrial sector - the second preferred candidate to reinvest into by our optimization criterion. An additional potential explanation for this unexpected inclusion is that the firms in the industrial sector are indeed reducing their carbon emissions. This is supported by the fact that the industrials sector covers a wide variety of firms, and despite our increased investment in this sector, our portfolio carbon footprint actually reduces over the years.

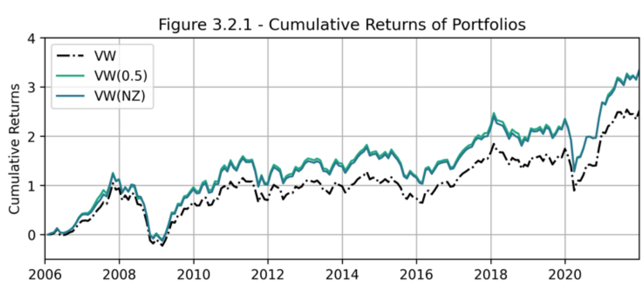


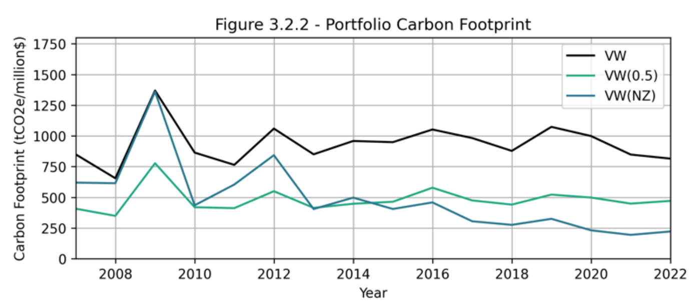


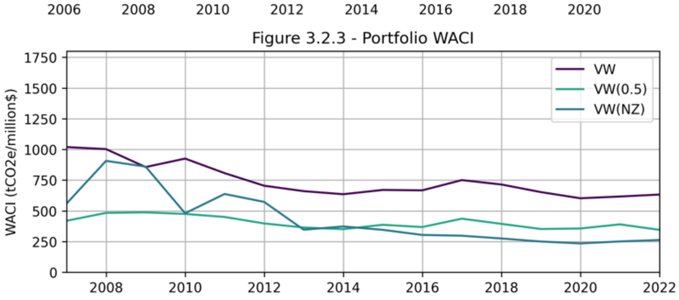
3.2 - Comparing all three benchmark decarbonization strategies, the possible cost of constructing a net zero portfolio

Table 3.2 summarizes the overall statistical metrics for all three portfolios. The VW(0.5) portfolio performs very closely to the net zero portfolio VW(NZ) and they both outperform the pure VW portfolio in various measures, with the VW(NZ) portfolio suffering less during the global financial crisis. From the portfolio performance perspective, VW(NZ) and VW(0.5) are equally matched. However, when looking at the evolution of carbon footprint in Figure 3.2.2, despite a spike in carbon emissions in 2009 that reaches the VW portfolio, the carbon emission was vastly reduced to around 200 $tCO_2/mln\$$ - two times lower than the final carbon footprint of the VW(0.5) portfolio. In the same figure, a similar spike is observed in 2009 for the MV(0.5) portfolio, but the overall reduction in carbon footprint is much less impressive than that of the VW(NZ) portfolio.

Table 3.2: VW vs VW(0.5) vs VW(NZ)			
Metric	**VW**	**VW(0.5)**	**VW(NZ)**
Annualized Mean Return	0.0958	0.1214	0.1216
Annualized Volatility	0.2074	0.2071	0.2073
Sharpe Ratio	0.4013	0.5308	0.5314
Minimum Return	-0.2662	-0.2627	-0.2618
Maximum Return	0.1853	0.1878	0.1882
Maximum Drawdown	1.2697	1.3631	1.3545
Period of Maximum Drawdown	2007/10/31 – 2009/02/28		

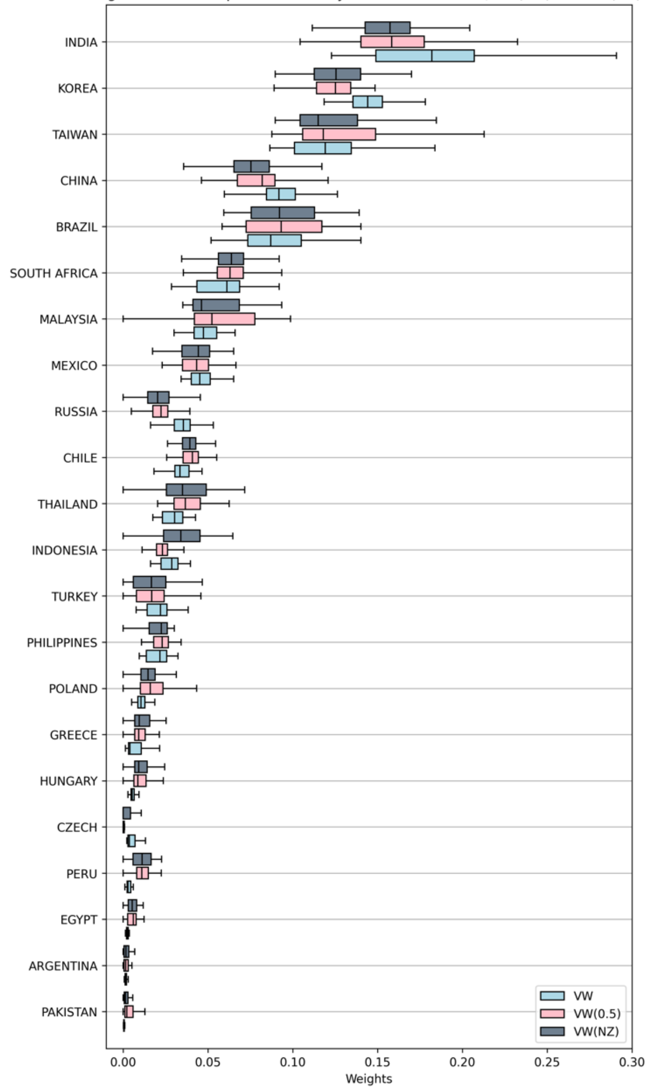






Since we have discussed in detail the sectoral weights reallocation for the VW and VW(0.5) portfolios, it is more interesting to look at the regional weight reallocation shown in Figure 3.2.4. India occupies more than 15% of portfolio over the years followed by South Korea and China. In terms of changes between the regions, our net zero portfolio divests from India,

Figure 3.2.4 - Comparative Country Distribution for VW, VW(0.5) and VW(NZ)



Korea, China and reallocates to Brazil, South Africa and other Asian countries. The VW(0.5) portfolio serves as an intermediate step between the pure VW and the VW(NZ) portfolios, with moderate adjustments in weights suggesting a progressive tightening of the carbon constraint, that leads to progressively larger shifts in country weights. Overall, both decarbonization strategies do not significantly alter the regional weights allocation, nor do they reduce the spread of the weight distribution compared to the standard value weighted portfolio.

In summary, both decarbonized strategies are cost-free, and even offer improved performance brought about by the exclusion of highly-polluting firms. Moreover, VW(NZ) portfolio not only generates good returns, but also delivers outstanding carbon emission reductions in the long term.

Appendix

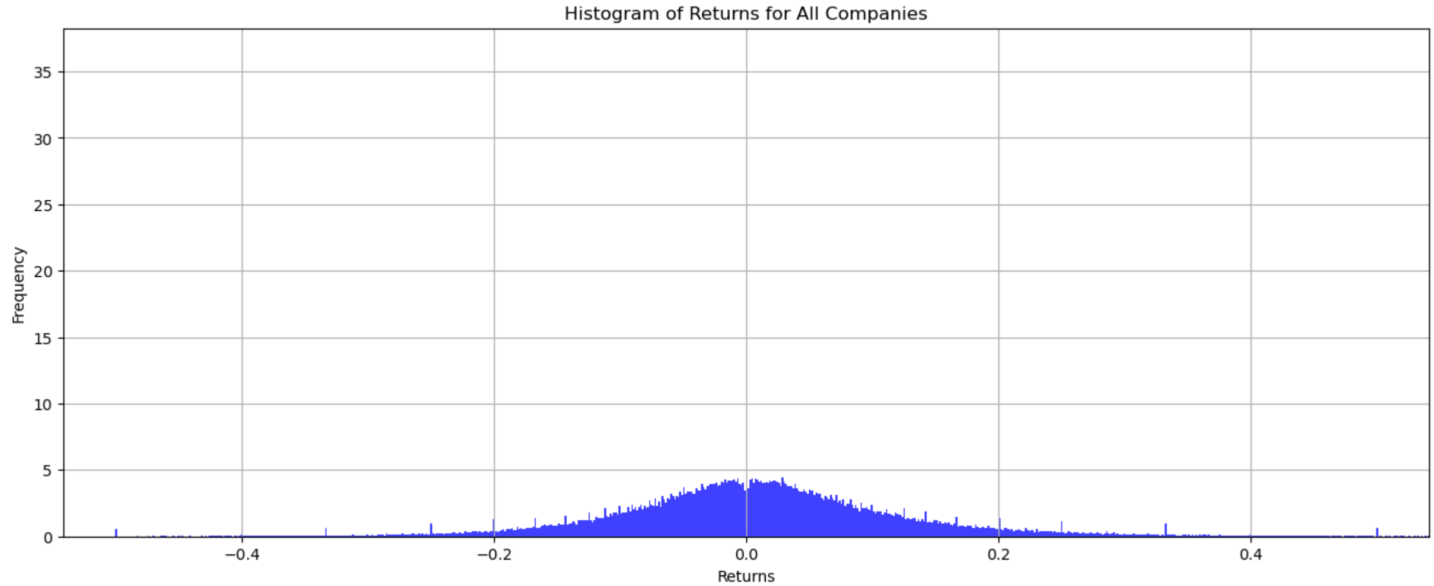
Table 4: All Portfolios: Evolution of WACI and Carbon Footprint $(tCO_2e/mln\ \$)$										
	MV		MV(0.5)		VW		VW(0.5)		VW(NZ)	
	WACI	CF	WACI	CF	WACI	CF	WACI	CF	WACI	CF
2006	850.6	828.0	628.9	360.7	1019.5	849.8	419.4	407.4	559.0	619.8
2007	1183.7	1154.7	739.7	287.5	1002.9	655.4	483.5	349.1	907.1	614.9
2008	1002.4	937.8	936.8	820.7	856.7	1369.6	487.6	777.5	860.3	1360.5
2009	1100.2	758.5	763.7	421.5	925.6	864.1	474.9	419.4	480.5	435.2
2010	862.9	406.7	735.5	309.8	807.2	764.4	450.4	412.0	637.5	604.2
2011	880.9	562.7	546.4	245.5	704.8	1059.7	397.6	550.0	573.2	842.9
2012	644.1	828.6	633.1	238.9	660.5	850.3	364.5	414.5	346.4	404.6
2013	862.8	2045.2	763.8	535.3	635.6	959.0	351.1	447.8	373.2	497.6
2014	1482.8	4148.6	856.6	982.5	670.3	949.1	386.6	463.9	345.6	405.3
2015	1615.9	6087.8	878.3	2339.3	667.1	1052.3	368.2	578.2	304.1	458.6
2016	573.1	559.7	573.1	559.7	750.4	982.8	436.5	474.8	297.7	305.1
2017	638.5	508.5	487.9	297.5	714.8	878.2	394.3	440.7	275.2	275.8
2018	541.7	666.3	295.3	287.9	652.9	1073.8	352.3	522.1	250.5	324.9
2019	488.6	490.3	344.0	279.2	602.5	999.1	356.5	498.2	234.8	231.4
2020	741.2	4879.2	307.1	238.3	616.9	848.2	390.2	448.9	251.1	194.4
2021	635.6	1427.4	635.5	1427.4	632.8	815.3	345.6	471.0	263.0	221.9

Appendix – Verification:

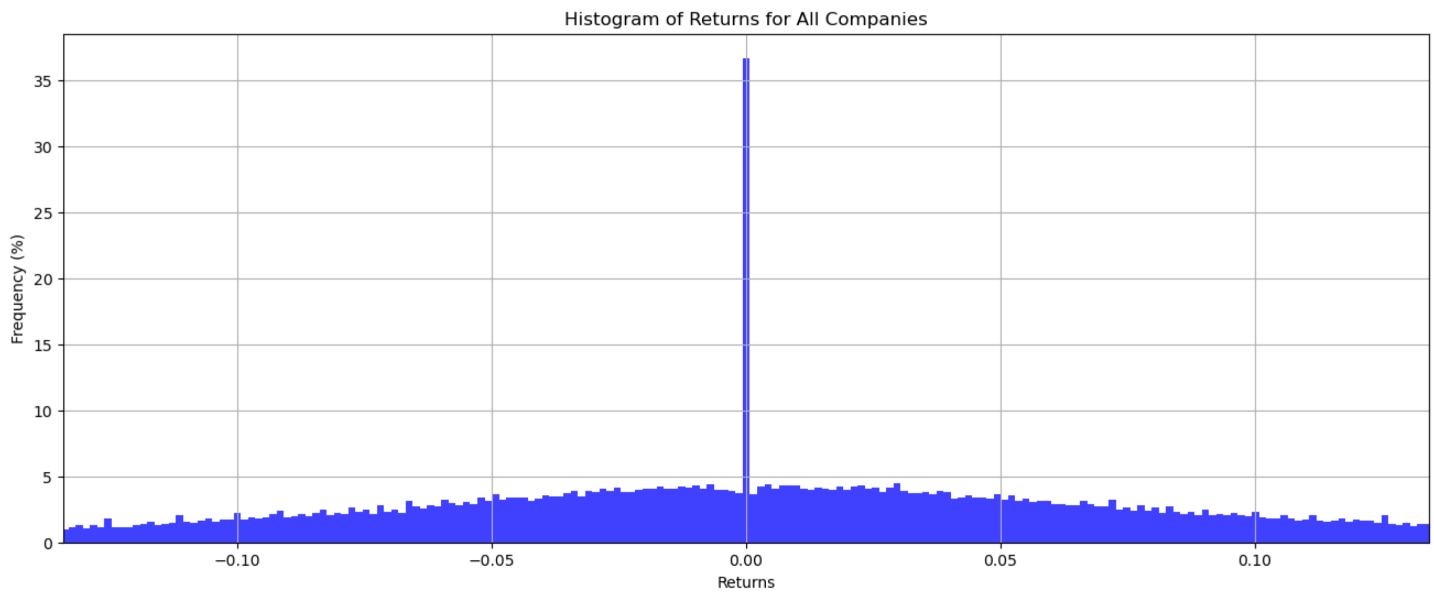
The Problem: The cumulative returns of the minimum variance portfolio are too high for emerging market.
Steps taken to remedy the problem:
1 – Ensuring data integrity
First, we inspect DS_RI_T_USD_M.xlsx for any obvious signs of bad data amongst the companies in the emerging markets (EM) universe, such as empty series, constant values, very low values, very high values. Next, we repeat this process for asset returns (simple return). Taking a percentage change inadvertently results in infinites, our procedures for handling bad observations in returns is:

1) Backfill the first observation with the second observation
2) Replace positive and negative infinities with NaN values
3) Replace all NaN values with 0

This approach results in a small number of extreme observations (less than 10) that can be filtered out by hand. Omitting those values presents us with a distribution of returns that does not appear particularly suspicious. What is surprising however is that returns exhibit an excess kurtosis of 14.2 and a positive skewness of 1.28.



Zooming in, we can see that a there is a peak of that returns are 0 (5% of all returns are 0), which is to be expected given that some assets do not exist throughout the entire sample.



These zero return assets must be filtered out in some way because they have low-to-no variance and will always be picked by the optimizer which aims to minimize the variance of our portfolio. We have tried various methods to filter out these assets:

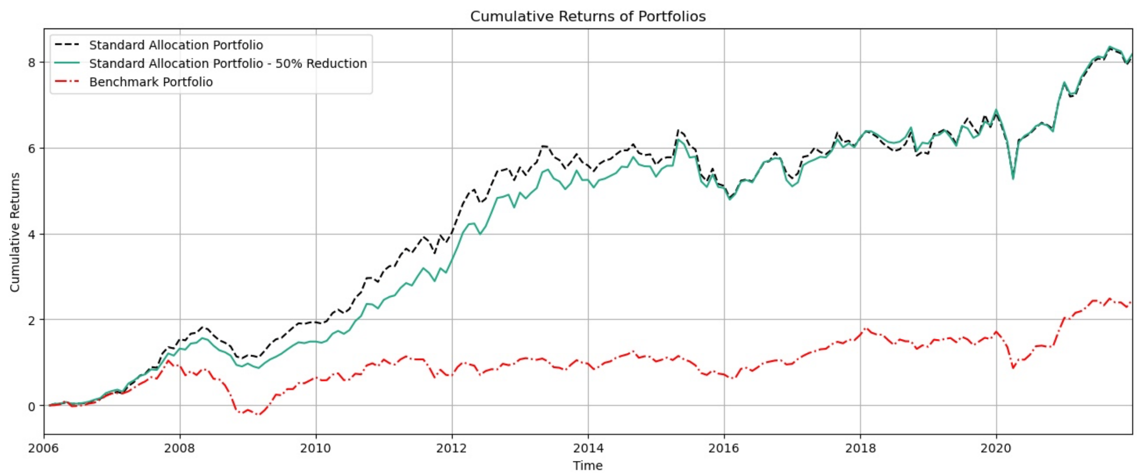
- **Initially**: Filtering out the assets that has December return equals 0. Each year has different number of assets, on average 490/507 assets are being optimized each year.
  - Not filtering resulted in extremely poor performance.
- **Subsequently**, we have tried adding various other filters, including:
  - Filtering out the asset if zero returns are frequent (number of zero returns >= N) in the last in-sample year. Each year has different number of assets, on average 500/507 assets are being optimized each year.
  - Filtering out penny stocks by setting a minimum threshold price below which the assets would not be considered (last known price).
  - Filtering out all assets that had any number of “extreme” returns in the last 5 years.
  - Various combinations of these filters.

In conclusion, the filter that seems the least intrusive is the one that filters out the zero-return assets in the last in-sample year. Applying it results in less excluded assets, but the cumulative return for the minimum variance portfolio with old/new filters is visually identical, even when combining multiple filters.

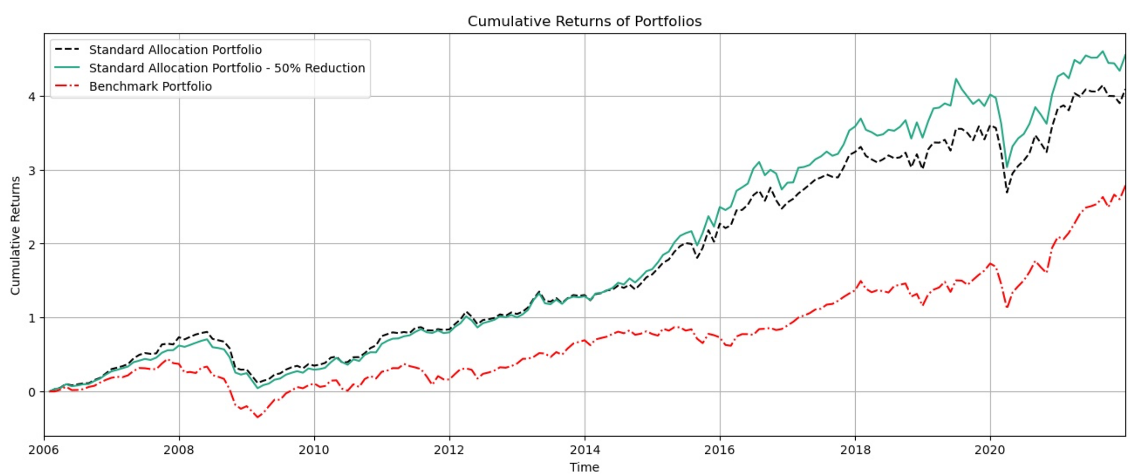
2 – Changing the Optimizer
We have gone over the code line by line many times over, verifying the optimization process and the performance tracking to be theoretically sound and strictly in-sample. Having exhausted all the potential sources of error we decided to try to use the cvxpy package instead of scipy.minimize that we had used previously. Besides being dramatically faster and resulting in (slightly) lower objective function values, the performance of the minimum variance portfolio remained, for all intents and purposes, unchanged. This was a sign that the problem did not stem from our optimization procedure, seeing as the whole optimization pipeline was completely rewritten.

3 – Looking at Other Regions
Finally, we wanted to see how our process would perform in other markets. We have solicited our classmates to share their performance with us but are yet to receive enough information to draw any conclusions. The performance of all the regions is presented below, with the decarbonized portfolio (not relevant to our problem) including scopes 1+2+3. Notably, cumulative returns for North America and Europe are reasonable. However, Pacific, Emerging Market and ACWI minimum variance portfolios are outperforming the benchmark.

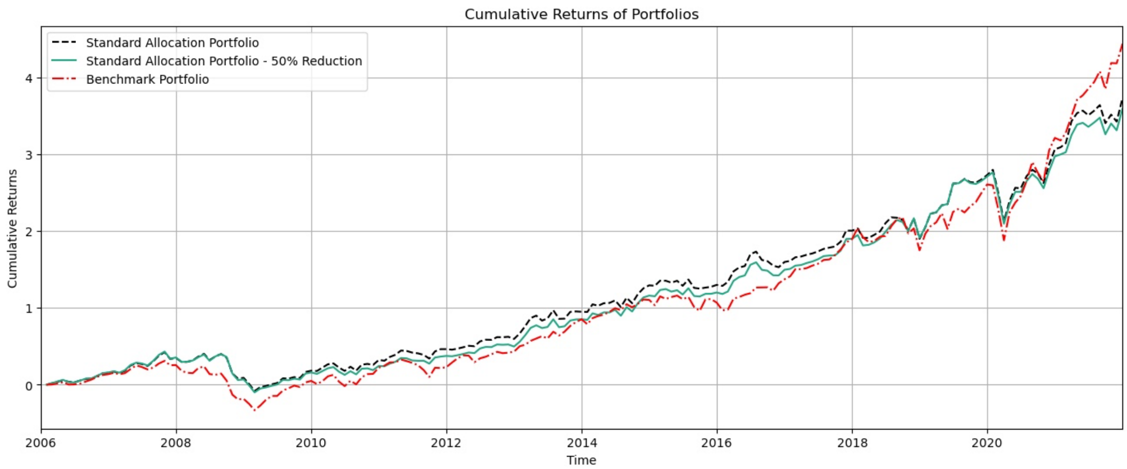
- **Emerging Markets** (our problematic portfolio)**:**



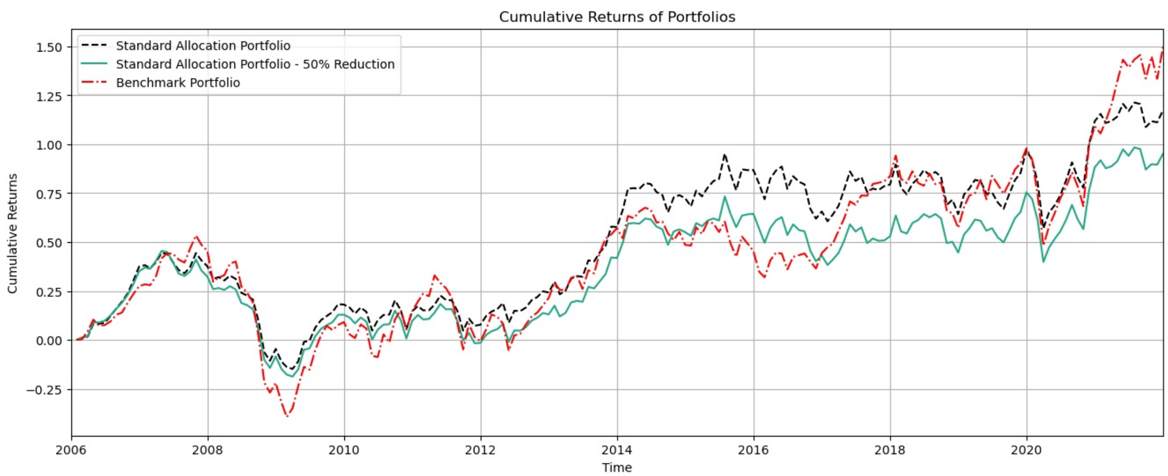
- **ACWI**:



- **North America:**



- **Europe:**



- **Pacific:**