6 DS ANALYSIS AND AI SCENARIOS FOR DS3 IN MOROCCO

6.1 Context and challenges

The Moroccan Demo Site is located in the Souss-Massa region, one of the most important agricultural basins of the country. The area is characterised by a semi-arid climate, recurrent droughts, and heavy pressure on groundwater resources due to irrigation for high-value crops such as citrus and vegetables. Overexploitation has led to declining water tables, soil salinisation, and increasing vulnerability of ecosystems.

The Demo Site aims to explore solutions that improve irrigation efficiency, diversify water sources, and promote sustainable land management. The main challenges identified include water scarcity, high energy demand for pumping, and socio-economic dependency of smallholder farmers on practices that may degrade soil and water resources.

6.2 Top 3 prioritised solutions

During the Moroccan regional workshop, stakeholders evaluated 17 candidate NBS and BES using the SureNexus MCA tool. Only three solutions surpassed the threshold score of 50, indicating their strong alignment with local needs and priorities (Figure 16):

- Agroforestry was the highest ranked option. It provides multiple benefits by improving soil fertility, enhancing biodiversity, and increasing resilience to drought through better water retention. Farmers also valued its potential for diversifying income sources.
- Subsurface rainwater harvesting was prioritised second. This practice reduces evaporation losses and enables more reliable water storage for agriculture, directly addressing water scarcity in semi-arid conditions.
- Conservation agriculture was the third solution above the threshold. Stakeholders highlighted its role in reducing soil erosion, improving soil organic matter, and decreasing reliance on chemical inputs.

Agroforestry and conservation agriculture are key nature-based strategies that enhance ecosystem functioning and climate resilience, while subsurface rainwater harvesting directly reinforces local water security. Both agroforestry and subsurface rainwater harvesting were tested across multiple demosites; however, the **DS3 demosite in Kenitra served as the central reference site for analysing seasonal irrigation dynamics in detail.**

At this demosite, the model enabled the calculation of Net Irrigation Requirements (NIR) and Gross Irrigation Requirements (GIR), using high-quality evapotranspiration measurements. In particular, **ET was estimated through the Penman-Monteith method**, which provides significantly more accurate and robust results than simplified empirical approaches such as Hargreaves, especially under variable coastal–Mediterranean climatic conditions.

For this reason, **DS3 became the main platform for understanding how mulching—as a core practice within conservation agriculture—can optimise water use, reduce irrigation demand, and improve energy efficiency within a WEFE Nexus framework.** The analysis demonstrates the potential of mulching to buffer soil moisture, reduce evaporation losses, and ultimately contribute to more resilient and sustainable irrigation management.

6.3 Ai scenario results and discussion

The Moroccan digital citrus demonstrator explores how different mulching levels and irrigation strategies affect water use, crop production, energy demand and potential GHG emissions for two mandarin varieties (Gharbaouia and Mahdia) and two orange varieties (Shamssia and Valencia). All scenarios are simulated under semi-arid climate conditions representative of the Souss-Massa region, where groundwater over-exploitation and rising pumping costs are critical issues. The AI WEFE Nexus model is used to quantify Gross Irrigation Requirement (GIR), Net Irrigation Requirement (NIR), harvest and derived efficiency indicators for each combination of variety and mulching factor.

Seasonal irrigation dynamics. Figures 33 and 34 present the **full time series of NIR and GIR** for mandarins and oranges, respectively, disaggregated by variety and mulching level. Time on the x-axis is expressed in days, covering the full annual cycle, while the y-axis shows irrigation depth in mm/day. Across all varieties, the curves exhibit a similar seasonal pattern: very low irrigation requirements in winter, a sharp increase at the onset of the dry season (around day 90–120), a plateau during the peak summer months, and a progressive decline towards the end of the growing season. This common shape reflects the strong climatic control on crop evapotranspiration at INRA-Kenitra and the fact that all citrus varieties share broadly comparable phenological stages.

In NECADA, mulching intensity is simulated through a Soil Evaporation Factor (0.7, 0.8, 0.9), which scales potential evaporation (pevap) to represent different levels of mulch efficiency. A **lower factor (e.g., 0.7) corresponds to a stronger reduction of soil evaporation, while higher factors (e.g., 0.9) represent weaker mulching**. These coefficients affect only the soil evaporation component of ETc and do not modify canopy cover or transpiration.

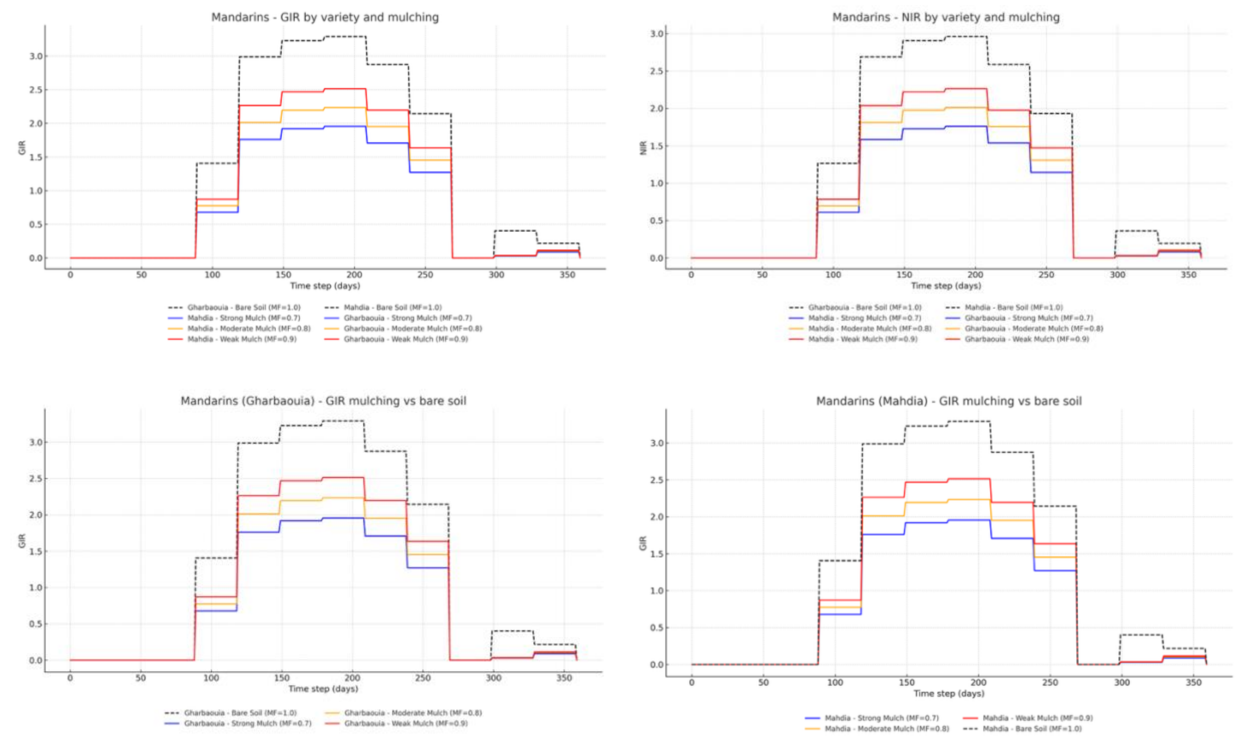

FIGURE 33. FULL TIME SERIES OF NIR AND GIR FOR MANDARINS DISAGGREGATED BY VARIETY AND MULCHING LEVEL.

The **Bare Soil (MF = 1.0)** case, represented as a dashed line, always lies above the mulched scenarios. This confirms that, **in the absence of surface protection, soil evaporation contributes substantially to total water demand**. In contrast, the **Strong Mulch (MF = 0.7), Moderate Mulch (MF = 0.8) and Weak Mulch (MF = 0.9)** scenarios show progressively **higher irrigation requirements as the mulch factor approaches 1.0**. In other words, **stronger mulching (MF = 0.7) achieves the largest reduction in NIR and GIR**, while weak mulching (MF = 0.9) still offers savings compared to Bare Soil but to a lesser extent.

For both mandarins and oranges, the results show a consistent hierarchy:

- **Strong Mulch (MF = 0.7)** delivers the **lowest annual NIR and GIR**, achieving substantial water savings relative to Bare Soil.
- **Moderate Mulch (MF = 0.8)** and **Weak Mulch (MF = 0.9)** form an intermediate group, progressively approaching the Bare Soil values as mulching intensity decreases.
- **Bare Soil (MF = 1.0)** yields the **highest irrigation demand**, representing the current “business-as-usual” benchmark without soil protection.

For mandarins, the difference between Strong Mulch and Bare Soil reaches several hundred mm per year, equivalent to a reduction of roughly one-third to almost half of the irrigation water applied, depending on the variety. Oranges display similar relative trends, confirming that mulching is a robust strategy across citrus cultivars.

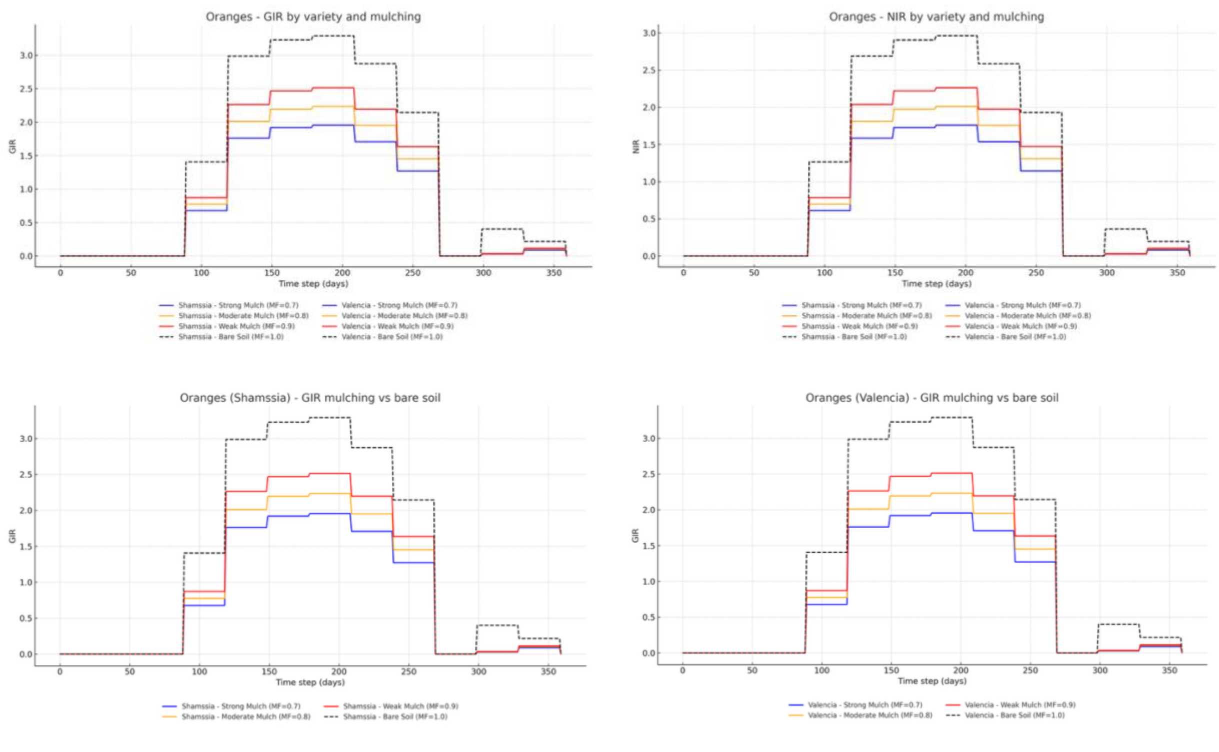

FIGURE 34. FULL TIME SERIES OF NIR AND GIR FOR ORANGES DISAGGREGATED BY VARIETY AND MULCHING LEVEL.

Differences between varieties at the same mulching level are comparatively modest, indicating that **mulching intensity is the primary driver of irrigation savings, while varietal effects are secondary**. This is important from a management perspective: farmers can retain their preferred commercial varieties while optimizing mulching practices to reduce water use.

Mulching delivers substantial water savings across all citrus varieties tested, as shown in Table 3. The **strongest mulching treatment (MF = 0.7) reduces irrigation demand by more than 40%**, representing the most effective strategy for increasing water-use efficiency. Even the **weakest mulching treatment reduces irrigation needs by nearly 30%,** demonstrating that any level of soil cover contributes meaningfully to reducing unproductive soil evaporation.

TABLE 3. WATER SAVED VS BARE SOIL FOR EACH TYPE OF MULCHING.

Scenario	GIR (mm/yr)	Water Saved vs Bare Soil
Strong Mulch (0.7)	282.3	**43%**
Moderate Mulch (0.8)	322.6	**35%**
Weak Mulch (0.9)	362.9	**27%**
Bare Soil (1.0)	496.5	0%

Harvest and water productivity. Figure 35 (above) summarises the **harvest (t/ha)** obtained for each variety and mulching level. Yields remain relatively stable across mulching factors, with only slight variations between Strong, Moderate and Weak Mulch scenarios. Importantly, there is **no systematic penalty in production under stronger mulching**; in several cases, Strong Mulch maintains or even slightly improves yields compared to Bare Soil, likely due to better soil moisture conservation and reduced water stress during the critical summer period.

Figure 35 (below) combines the information on water use and production to derive **Water Productivity (kg fruit/m³ of irrigation water).** Here, the benefits of mulching become particularly evident. Because harvest remains similar while NIR and GIR are reduced, mulched scenarios show a pronounced increase in water productivity compared to Bare Soil:

- **Strong Mulch (MF = 0.7)** consistently achieves the **highest water productivity** for both mandarins and oranges.
- **Moderate and Weak Mulch** present intermediate values, still clearly superior to Bare Soil.
- **Bare Soil** exhibits the lowest water productivity, confirming that a substantial fraction of applied water is lost as non-productive soil evaporation.

This result is central from a WEFE perspective: **mulching allows the system to produce the same amount of food with significantly less water**, thereby easing pressure on over-exploited aquifers and increasing resilience under drought.

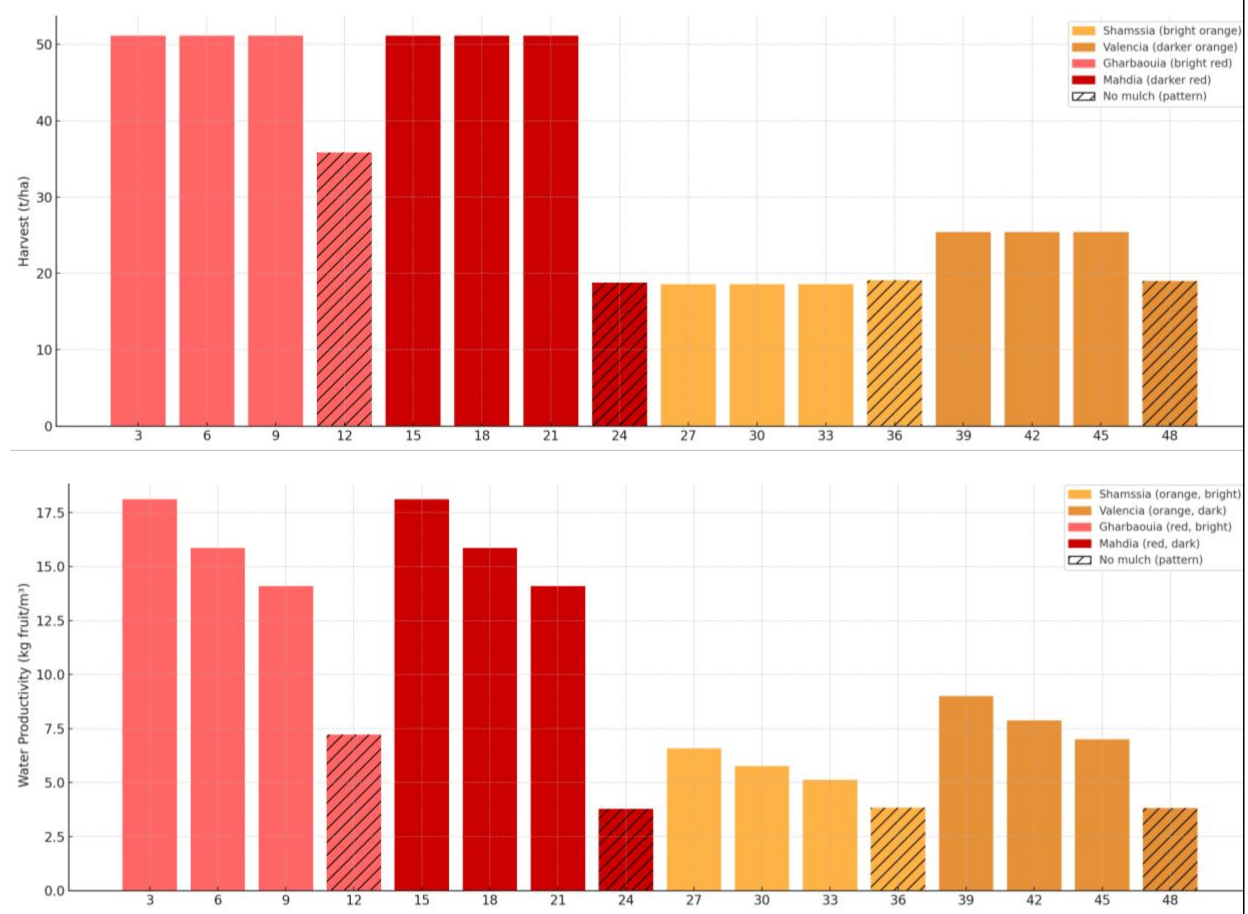

FIGURE 35. (ABOVE) HARVEST (T/HA) OBTAINED FOR EACH VARIETY AND MULCHING LEVEL ACROSS ALL SCENARIOS. (BELOW) WATER PRODUCTIVITY FOR ORANGES AND MANDARINES FOR EACH VARIETY AND MULCHING LEVEL ACROSS ALL SCENARIOS.

Energy use and GHG intensity. Although all final simulations for the Morocco demonstrator are run assuming 100% solar pumping, the model outputs for pumping energy can be interpreted in two complementary ways:

1. As the **actual renewable energy demand** that must be covered by onsite photovoltaic systems.
2. As the **avoided grid electricity consumption**, which can be translated into potential GHG savings.

The **WEFE-Energy combined panel** (Figure 36) integrates water use, crop productivity, energy consumption, and associated GHG implications into a single comparative visualization, allowing a **holistic assessment of each mulching scenario**.

By juxtaposing irrigation demand (NIR/GIR) with pumping energy requirements and the resulting energy intensity per ton of fruit, the panel highlights **how soil management practices directly influence the interconnected dimensions of the WEFE Nexus**. Strong and Moderate Mulch scenarios consistently occupy the most favourable positions, showing simultaneously lower water use, reduced pumping energy, and higher water productivity, while maintaining stable yields. In contrast, the **Bare Soil scenario demonstrates the strongest trade-offs**, with high irrigation requirements leading to elevated energy consumption and poorer overall WEFE performance.

By consolidating these indicators, the combined panel makes explicit how **interventions that reduce unproductive water losses—such as mulching—generate cascading benefits** across water, energy, food, and climate dimensions, reinforcing their strategic value for integrated resource management.

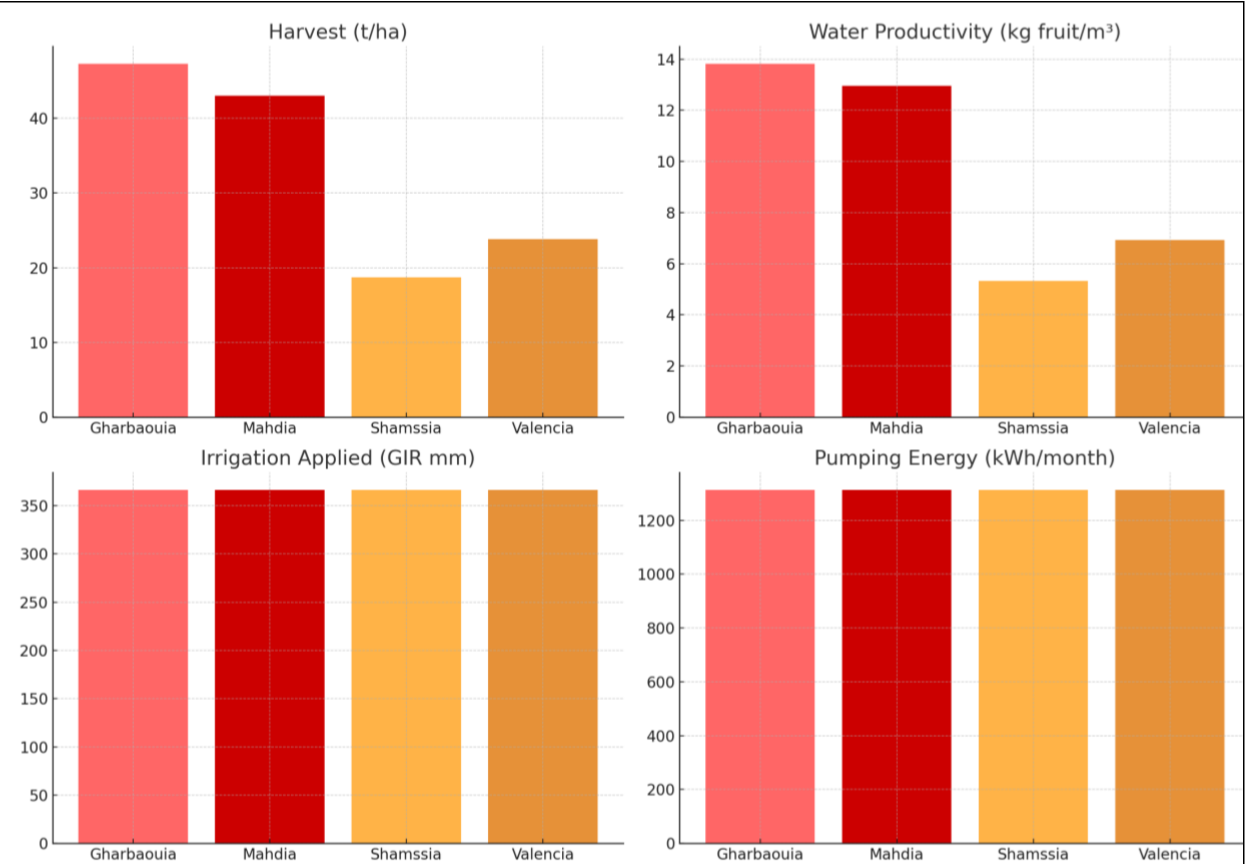

FIGURE 36. WEFE ENERGY COMBINED PANEL (AVERAGED BY VARIETY).

The analysis of average monthly pumping energy (Figure 37) clearly reflects the strong influence of soil management practices on irrigation requirements and, consequently, on energy consumption. Across all citrus varieties, **scenarios with mulching consistently require less energy to pump irrigation water than the bare-soil**

baseline. Strong Mulch (MF = 0.7) exhibits the lowest energy demand, averaging **around 88 kWh/month**, followed by Moderate Mulch (MF = 0.8) at **98 kWh/month** and Weak Mulch (MF = 0.9) at **108 kWh/month**. In contrast, the Bare Soil scenario (MF = 1.0) requires approximately **142 kWh/month**, reflecting the substantial amount of water needed to compensate for unproductive soil evaporation. These results demonstrate that **mulching can reduce irrigation-related energy use by 23-37%,** depending on the intensity of soil cover.

Because crop yields remain stable across mulching treatments, the reduction in pumping energy directly enhances the overall efficiency and climate performance of the irrigation system. Lower water demand translates into reduced operational costs, minimized dependence on grid electricity, and lower GHG emissions where fossil-based energy is used. In a WEFE Nexus perspective, mulching therefore emerges as a cost-effective and environmentally beneficial practice that simultaneously improves water and energy efficiency without compromising food production, reinforcing its relevance for climate-resilient agricultural management in semi-arid regions such as Kenitra.

Figure 37 presents the energy intensity (kWh/ton of fruit) for each variety and mulching level. Because mulching reduces total water pumped while yields remain similar, energy intensity follows the same pattern as water productivity but in inverse form:

- Strong Mulch shows the **lowest kWh/ton**, meaning less energy is required per unit of harvest.
- Bare Soil requires the **highest energy per ton**, as more water must be lifted to achieve comparable production.

Figure 38 translates these energy demands into **GHG intensity** under two hypothetical supply options: (i) if all pumping were supplied by conventional grid electricity, and (ii) if the same energy demand were met by solar panels. Bars representing grid emissions are much higher than those for solar, reflecting the large difference between emission factors. The gap between the two bars for each scenario can be interpreted as a **GHG mitigation potential associated with switching from grid to solar energy**.

Even within the solar case, **Strong Mulch clearly minimises emissions per ton of fruit because less energy is required overall**. Thus, **combining mulching with solar pumping offers a double climate benefit: reduced energy demand and a low-carbon energy source.**

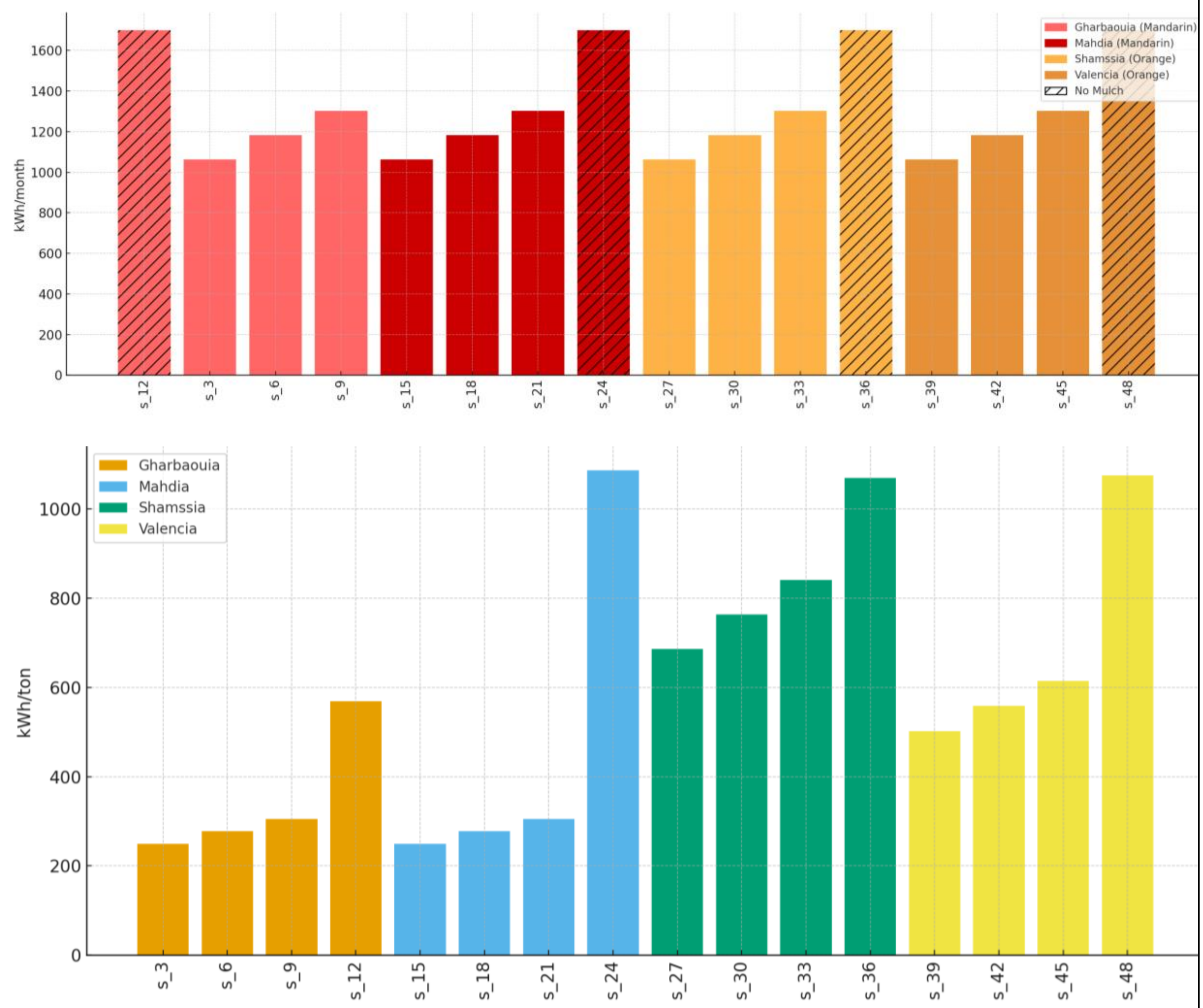

Figure 37. (Above) Average monthly pumping energy per scenario and, (Below) energy intensity (kWh per ton of fruit).

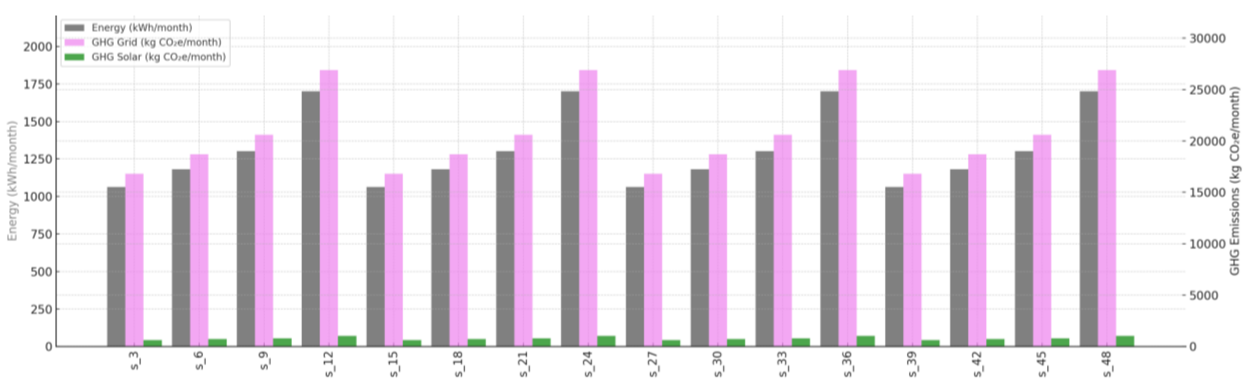

Figure 38. Energy vs GHG emissions per scenario.

WEFE performance and scenario comparison. The suite of indicators is synthesised in Composite indices and **WEFE radar plots** (Figure 39). **Mandarins obtain a higher WEFE composite index than oranges** primarily because their **irrigation requirements are lower for the same mulching conditions, which leads to reduced pumping energy and lower associated GHG intensity**. Since yields remain comparable across varieties, the mandarins benefit more from the water-saving effects of mulching, resulting in higher water productivity and lower energy intensity per ton of fruit. These combined advantages strengthen their performance across all WEFE dimensions—Water, Energy, Food, and Ecosystems—allowing mandarins to achieve consistently higher composite scores.

In contrast, **oranges show slightly higher GIR/NIR values and therefore higher energy use, which reduces their relative WEFE performance** even under similar management practices.

When aggregated into a **WEFE composite index and ranked (**Figure 39 and Figure 40), scenarios with Strong Mulch (MF = 0.7) for both mandarins and oranges systematically occupy the top positions. Bare Soil cases appear at the bottom of the ranking. This confirms that mulching is not only a water-saving measure but also an integrated WEFE optimisation strategy for the digital citrus demonstrator.

Each axis of the radar represents one dimension—Water, Energy, Food (yield/water productivity) and Ecosystems (proxied by reduced abstraction and lower GHG intensity). Indicators are normalised so that higher values correspond to better performance. In these radars:

- **Strong Mulch scenarios occupy the largest polygon**, indicating a balanced improvement across all WEFE dimensions.
- Moderate and Weak Mulch form intermediate shapes, better than Bare Soil but not as pronounced as Strong Mulch.
- Bare Soil appears as the smallest polygon, with particularly poor values in Water and Energy axes due to the elevated irrigation and pumping requirements.

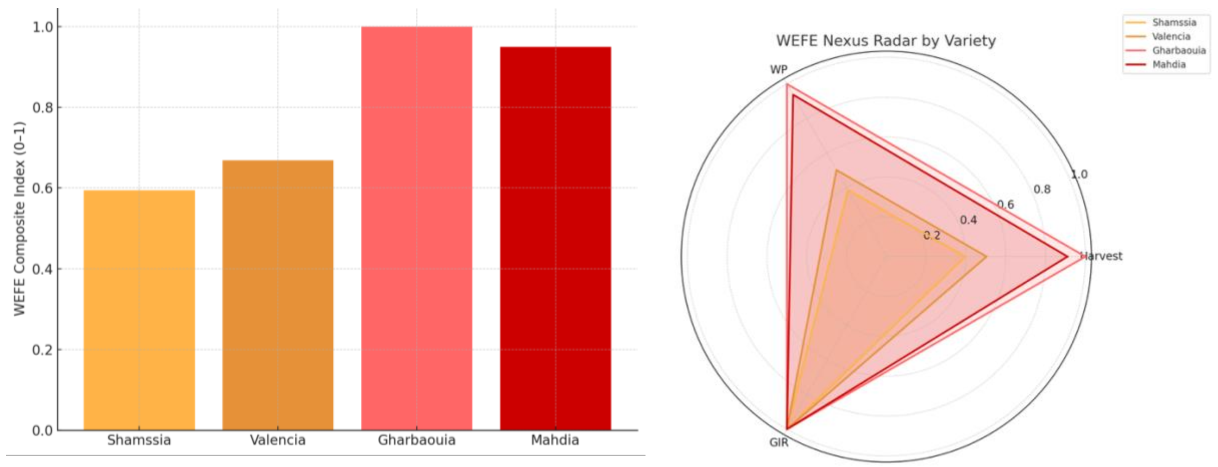

FIGURE 39. (LEFT) WEFE COMPOSITE INDEX BY VARIETY, (RIGHT) WEFE NEXUS RADAR BY VARIETY.

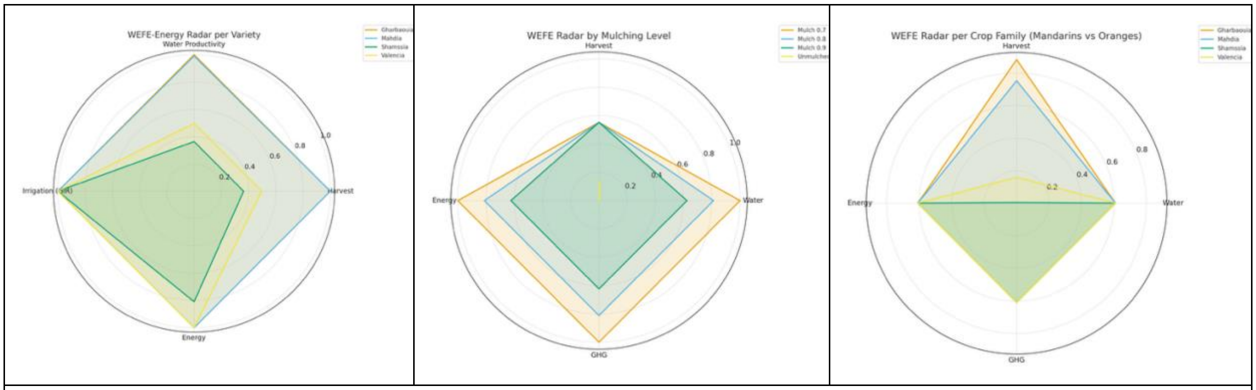

FIGURE 40. WEFE RADAR PER VARIETY (LEFT), BY MULCHING LEVEL (CENTER) AND PER CROP FAMILY (RIGHT).

6.4 AI WEFE Nexus Trade-off Analysis for Morocco Digital Citrus Demonstrator

In this section, the simulations are interpreted from a multi-criteria and trade-off perspective, using MCDA heatmaps and Delta-Heatmaps to support decision-making.

MCDA and weighted performance. Figure 41 presents a **WEFE MCDA heatmap** where each row corresponds to a scenario (defined by variety and mulching factor) and each column to a criterion—Water use, Water productivity, Energy intensity, GHG intensity, and Food production. Cell colours reflect normalised performance, ranging from red (worst) to green (best). Additional panels apply different weighting schemes (e.g. Balanced, Water Priority, Climate Priority). Key insights are:

- Under **Balanced weighting**, scenarios with **Strong Mulch (MF = 0.7)** for both mandarins and oranges achieve the highest composite scores. They combine low irrigation demand, good yields, and reduced energy/GHG intensity.
- Under **Water-Priority weighting**, Strong and Moderate Mulch still dominate, as they provide the greatest reduction in NIR and GIR without sacrificing production.
- Under **Climate-Priority weighting**, the ranking is largely controlled by energy and GHG intensity. Again, mulched scenarios—especially those with Strong Mulch—perform best, while Bare Soil cases show the lowest scores due to high pumping requirements.

The heatmap therefore confirms that the **qualitative conclusions are robust to different policy priorities**: irrespective of whether the emphasis is on water saving, climate mitigation, or a balanced WEFE perspective, **mulched scenarios consistently outperform Bare Soil.**

FIGURE 41. (ABOVE) WEFE GHG HEATMAP (HATCHED = UNMULCHED SCENARIOS). (BELOW) WEFE COMPOSITE INDEX HEATMAP.

Trade-offs and Delta-Heatmap. The trade-off shown in Figure 42, comparing **Water Productivity (kg fruit/m³) and Energy Intensity (kWh/ton)** illustrates a strong and consistent relationship between soil management practices and overall WEFE performance.

Scenarios with mulching, particularly Strong Mulch (MF = 0.7) and Moderate Mulch (MF = 0.8), cluster in the desirable region of the graph, showing **high water productivity combined with low energy intensity**. This reflects the dual benefit of reducing unproductive soil evaporation: less water is required for irrigation, and therefore less energy is needed for pumping, while yields remain stable. Weak Mulch (MF = 0.9) scenarios occupy an intermediate position, still improving efficiency compared to Bare Soil but with less pronounced benefits. In contrast, **Bare Soil (MF = 1.0)** scenarios fall clearly in the unfavourable quadrant, where **low water productivity coincides with high energy intensity**, highlighting the compounding inefficiencies associated with exposed soil. The trade-off plot therefore makes the WEFE synergy explicit: practices that save water also save energy, reduce emissions, and enhance productivity, demonstrating that mulching creates a win-win pathway rather than forcing a trade-off between water efficiency and energy demand.

To highlight trade-offs more explicitly, Figure 43 displays a **Delta-Heatmap**, where all scenarios are compared against a chosen reference configuration (e.g. a representative Bare Soil case with grid pumping). Positive values (green) indicate an improvement relative to the reference; negative values (red) indicate deterioration. The Delta-Heatmap reveals three central patterns:

i. **Water vs. Food** – Moving from Bare Soil to mulched scenarios delivers large positive deltas in Water (less irrigation per hectare) with **neutral or slightly positive deltas in Food**, meaning that yield is preserved while water use falls. This confirms that there is **no water-food trade-off**; instead, mulching creates a win–win situation.

ii. **Water & Energy vs. Implementation Effort** – All mulched scenarios show strong improvements in Energy and GHG intensity relative to the reference. However, increasing mulch intensity from MF = 0.8 to 0.7 implies more material and maintenance. The Delta-Heatmap helps visualise that **most of the benefit is already captured at MF = 0.8**, while MF = 0.7 offers additional gains but with diminishing returns. This can guide farmers who face budget or labour constraints.

iii. **Climate benefits of solar pumping** – When the reference is assumed to be a grid-powered Bare Soil scenario, all solar-pumped, mulched options show very large positive deltas in GHG. This illustrates the **mitigation leverage of coupling soil-moisture management with renewable energy.**

Overall, the Delta-Heatmap makes explicit that **there is no single “perfect” scenario**, but a small set of clearly superior options. For policy and extension purposes, the most robust recommendations are:

a. Promote **mulching as a core water-saving and climate-mitigation practice** for citrus orchards, prioritising Strong or Moderate Mulch depending on local constraints.

b. Encourage the **progressive replacement of grid-powered pumping by solar pumping**, to capture the large GHG reductions indicated in the analysis.

c. Use the **WEFE composite index and MCDA rankings** as transparent tools to communicate these trade-offs to farmers, irrigation agencies and regional authorities.

Together, Sections 6.3 and 6.4 show how the AI WEFE Nexus tool and Digital Twin approach can translate detailed simulation outputs (NIR, GIR, yield, energy, GHG) into clear, policy-relevant evidence for optimising irrigation and mulching strategies in the Moroccan digital citrus demonstrator.

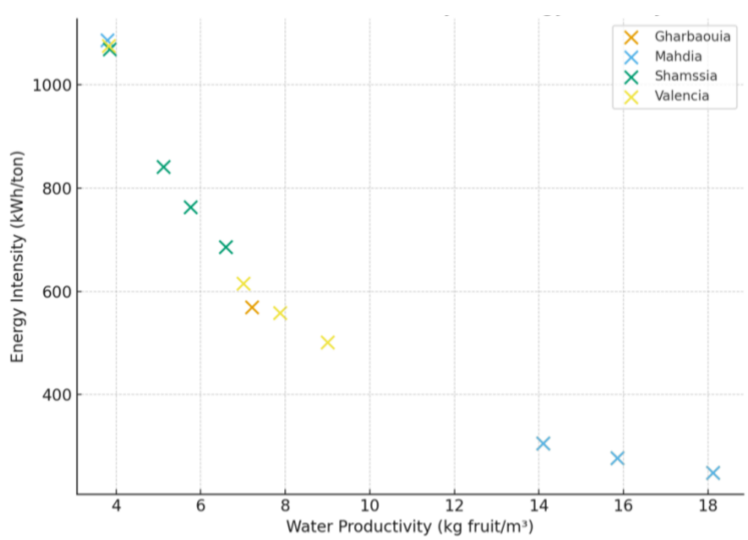

FIGURE 42. TRADE-OFF: WATER PRODUCTIVTY VS ENERGY INTENSITY.

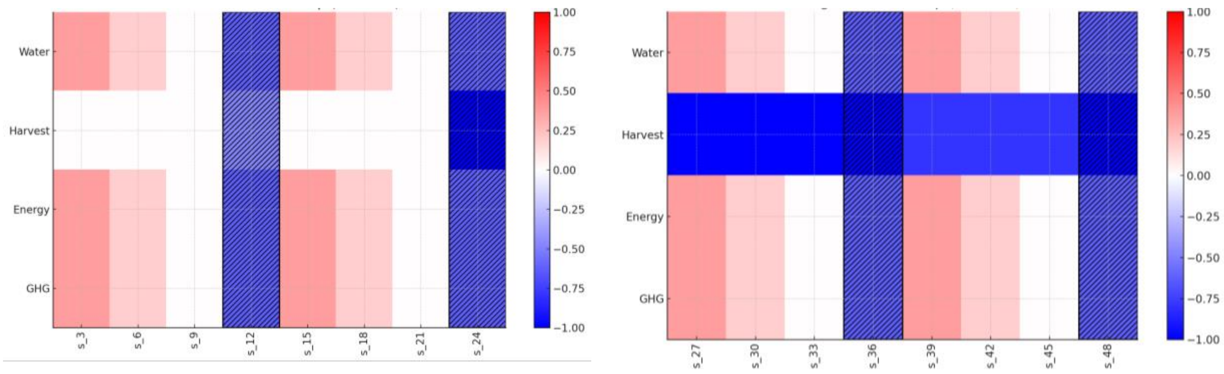

FIGURE 43. DELTA HEATMAP FOR MANDARINES (LEFT) AND ORANGES (RIGHT).

Finally, Figure 44 summarizes the full **WEFE Nexus Composite Radar for all 16 scenarios**, each one plotted individually so you can directly compare the WEFE performance footprint of:

- Water efficiency
- Harvest performance
- Energy efficiency
- GHG mitigation

The figure you see above includes all scenarios from s_3 to s_{48}, grouped by crop and mulching configuration.

Best WEFE profiles: s_3, s_6, s_{15}, s_{18}. These show almost perfect squares touching the outer 1.0 circle. They represent the **ideal WEFE NEXUS configurations**:

- Mandarins
- Mulched 0.7–0.8
- Highest harvest
- Lowest water & energy use
- Lowest GHG

Worst WEFE Profiles: s_{12}, s_{24}, s_{36}, s_{48}. These radars collapse toward the center, and are clearly non-viable in WEFE terms, indicating:

- Inefficient water use
- High energy → high GHG
- Low harvest (especially oranges)
- No mulching

Oranges vs Mandarins. Oranges (especially Shamssia) occupy the central low-performance region, with much worse harvest and overall WEFE outcome. Mandarins have balanced radars with strong harvest contribution.

Mulching effect (across all radars). Mulching expands the entire radar footprint outward, as a clear WEFE improvement. Mulched scenarios show:

- Better water point
- Better energy
- Better GHG
- Often equal or better harvest

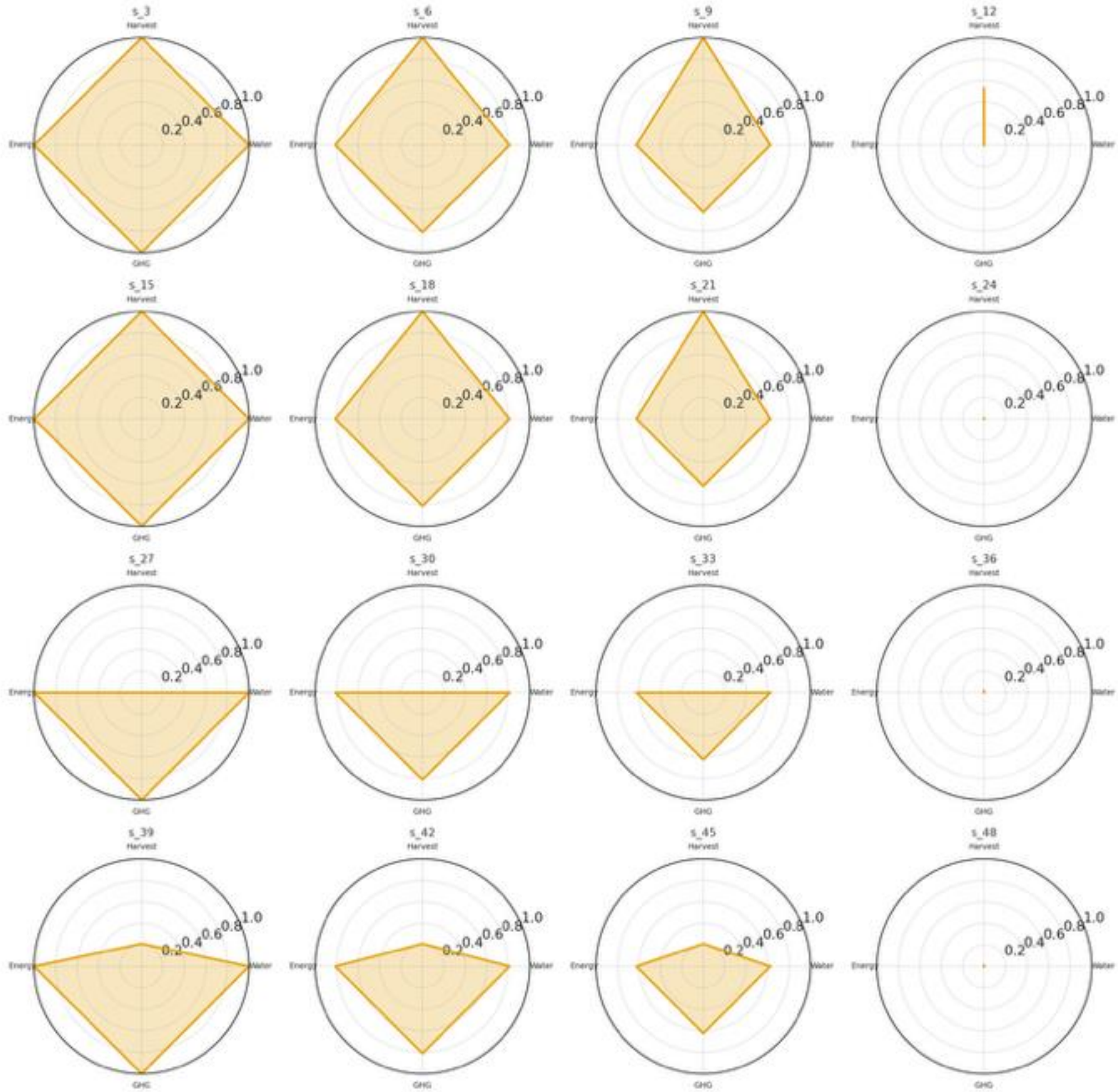

FIGURE 44. WEFE NEXUS COMPOSITE RADAR PER SCENARIO.