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**POSTGRADUATE PROGRAM
"BIOECONOMY, CIRCULAR ECONOMY & SUSTAINABLE DEVELOPMENT"**

METHODOLOGY FOR ASSESSING & PRIORITIZING INVESTMENTS IN ELECTRICITY DISTRIBUTION NETWORKS AGAINST CLIMATE CHANGE

Kairous Rozalia

Piraeus, January, 2024

ΤΜΗΜΑ
ΟΙΚΟΝΟΜΙΚΗΣ ΕΠΙΣΤΗΜΗΣ
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«Δηλώνω υπεύθυνα ότι το έργο που εκπονήθηκε και παρουσιάζεται στην υποβαλλόμενη διπλωματική εργασία, για τη λήψη του μεταπτυχιακού τίτλου σπουδών, στη «*Βιοοικονομία, Κυκλική Οικονομία και Βιώσιμη Ανάπτυξη*» με τίτλο:

ΜΕΘΟΔΟΛΟΓΙΑ ΑΞΙΟΛΟΓΗΣΗΣ ΚΑΙ ΠΡΟΤΕΡΑΙΟΠΟΙΗΣΗΣ ΕΠΕΝΔΥΣΕΩΝ ΣΕ ΔΙΚΤΥΑ ΔΙΑΝΟΜΗΣ ΗΛΕΚΤΡΙΚΗΣ ΕΝΕΡΓΕΙΑΣ ΕΝΑΝΤΙ ΤΗΣ ΚΛΙΜΑΤΙΚΗΣ ΑΛΛΑΓΗΣ

έχει γραφτεί από εμένα αποκλειστικά στο σύνολό της. Δεν έχει υποβληθεί ούτε εγκριθεί στο πλαίσιο κάποιου άλλου μεταπτυχιακού προγράμματος ή προπτυχιακού τίτλου σπουδών στην Ελλάδα ή στο εξωτερικό, ούτε είναι εργασία ή τμήμα εργασίας ακαδημαϊκού ή επαγγελματικού χαρακτήρα.

Δηλώνω επίσης υπεύθυνα ότι οι πηγές στις οποίες ανέτρεξα για την εκπόνηση της συγκεκριμένης εργασίας αναφέρονται στο σύνολό τους, κάνοντάς πλήρη αναφορά στους συγγραφείς, τον εκδοτικό οίκο ή το περιοδικό, συμπεριλαμβανομένων και των πηγών που ενδεχομένως χρησιμοποιήθηκαν από το διαδίκτυο. Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του πτυχίου μου.»

ΡΟΖΑΛΙΑ ΚΑΪΡΟΥΣ

ΕΥΧΑΡΙΣΤΙΕΣ

Στους γονείς μου:
Κάθε τι καλό που έχω πάρει, πρώτα το χρωστώ στην οικογένειά μου.
Καθώς βρίσκομαι στο κατώφλι ενός νέου κεφαλαίου μετά και από αυτό το εκπαιδευτικό ταξίδι κουβαλάω μαζί μου τα ανεκτίμητα μαθήματα ανθεκτικότητας και αποφασιστικότητας που μου μεταδώσατε. Είμαι βαθιά ευγνώμων για την επιμονή, υπομονή, τις θυσίες, και πάνω απ' όλα για την ακλόνητη αγάπη σας, που με ώθησαν σε αυτό το ορόσημο και ανυπομονώ να σας κάνω περήφανους στην επόμενη στάση της πορείας μου.

Στον άνθρωπο μου: Καθώς μοιραζόμαστε μια απαιτητική καθημερινότητα, η ενθάρρυνσή σου είναι για εμένα καθοριστική, ώστε να ανταποκρίνομαι στις προκλήσεις του ακαδημαϊκού & εργασιακού μου χώρου και είμαι ευγνώμων για την σταθερή υποστήριξη σου σε κάθε βήμα μου.

Στην Καθηγήτρια μου, Κωνσταντίνα Κοτταρίδη: Η αφοσίωσή σας στη διδασκαλία άφησε ανεξίτηλο σημάδι στο ακαδημαϊκό μου ταξίδι. Μέσα από συναρπαστικές διαλέξεις, σχόλια και γνήσιο ενδιαφέρον, με ενέπνευσε να αναπτύξω βαθύτερη κατανόηση αυτού του επιστημονικού πεδίου θεμάτων. Σας ευχαριστώ για την ακλόνητη καθοδήγηση.

Στην Συνεργάτη μου, Κατερίνα Γ.: Η αρωγή σου κατά την διάρκεια της πορείας μου, της οποίας κομμάτι αποτελεί η συγκεκριμένη εργασία, υπήρξε καθοριστική. Τόσο η γενναιοδωρία σου στην ανταλλαγή τεχνογνωσίας όσο και η καθοδήγηση σου, επιτάχυναν την επαγγελματική μου ανάπτυξη αλλά και την ολοκλήρωση του εκπαιδευτικού αυτού κύκλου μου. Είμαι τυχερή για τη συνεργασία μας και εκφράζω τις ευχαριστίες μου για τη συνεχή σου ενθάρρυνση.

ΜΕΘΟΔΟΛΟΓΙΑ ΑΞΙΟΛΟΓΗΣΗΣ & ΠΡΟΤΕΡΑΙΟΠΟΙΗΣΗΣ ΕΠΕΝΔΥΣΕΩΝ ΣΕ ΔΙΚΤΥΑ ΔΙΑΝΟΜΗΣ ΗΛΕΚΤΡΙΚΗΣ ΕΝΕΡΓΕΙΑΣ ΕΝΑΝΤΙ ΤΗΣ ΚΛΙΜΑΤΙΚΗΣ ΑΛΛΑΓΗΣ

Σημαντικοί Όροι: Κλιματική Αλλαγή, Δίκτυο Ηλεκτρικής Ενέργειας, Ανθεκτικότητα, Προταιρεοποίηση, Επενδύσεις, Πολυκριτηριακή Ανάλυση, Βάρη Κριτηρίων

Περίληψη

Η Κλιματική Αλλαγή και τα ολοένα αυξανόμενα σε συχνότητα, ένταση και διάρκεια ακραία καιρικά φαινόμενα που παρουσιάζονται λόγω αυτής είναι ένας σημαντικός παράγοντας που επηρεάζει όλη την αλυσίδα της ενέργειας, ιδιαίτερα δε τα δίκτυα ηλεκτρικής ενέργειας. Οι υποδομές αυτές, αν και έχουν πετύχει μεγάλους βαθμούς αξιοπιστίας, δεν έχουν την ικανότητα να αντιμετωπίζουν αποτελεσματικά απρόβλεπτες ακραίες καταστάσεις που οφείλονται συνήθως σε φαινόμενα όπως θυελλώδεις άνεμοι, πλημμύρες, έντονες χιονοπτώσεις, πυρκαγιές.

Οι Διαχειριστές Διανομής, σε διεθνές επίπεδο, λόγω της κρισιμότητας του ρόλου τους για αδιάλειπτη παροχή ενέργειας στους καταναλωτές, και καθώς η πλειονότητα των διαταραχών έχει επιπτώσεις σε επίπεδο διανομής, λαμβάνουν πρωτοβουλίες και μέτρα για την αύξηση της ανθεκτικότητας των δικτύων έναντι των ιδιαίτερα δυσμενών καιρικών φαινομένων, αλλά και για την προσαρμογή τους στην Κλιματική Αλλαγή. Η ανθεκτικότητα του συστήματος περιλαμβάνει την ικανότητα του να ανακάμπτει ταχέως μετά την εμφάνιση γεγονότων, και να προσαρμόζει τη λειτουργία και τη δομή του, ώστε να μετριάσει τις επιπτώσεις τους τόσο στις υποδομές του όσο και στην λειτουργία του.

Στη δραστηριότητα της λειτουργίας και συντήρησης σημαντικό μέτρο αποτελούν οι επενδύσεις σε συγκεκριμένες κατηγορίες έργων, όπως η υπογειοποίηση εναέριων γραμμών, η ανακατασκευή στοιχείων του δικτύου με πιο ανθεκτικά υλικά, η μεταφορά κρίσιμων εγκαταστάσεων σε λιγότερο ευάλωτες περιοχές, κλπ. Οι επενδύσεις αυτές απαιτούν σημαντικά επενδυτικά κεφάλαια με αξιοσημείωτη πολλές φορές επίδραση στην τελική τιμή του καταναλωτή. Τα κριτήρια που παρουσιάζονται για την προτεραιοποίηση της διάθεσης των κονδυλίων σε έργα βελτίωσης της ανθεκτικότητας των δικτύων διανομής και προσαρμογής τους στην Κλιματική Αλλαγή βασίζονται κυρίως στους άξονες της βιώσιμης ανάπτυξης, τον περιβαλλοντικό και τον κοινωνικό.

Η παρούσα εργασία εξετάζει τους παράγοντες και επιμέρους κριτήρια που πρέπει να λαμβάνονται υπόψιν για την προτεραιοποίηση των επενδύσεων με σκοπό την αύξηση της ανθεκτικότητας των δικτύων και την μακροχρόνια αντιμετώπιση της Κλιματικής Αλλαγής. Ταυτόχρονα, αναλύεται το μεθοδολογικό μοντέλο λήψης αποφάσεων για την αξιολόγηση και προτεραιοποίηση αυτών των επενδύσεων, που στηρίζεται στη λογική της πολυκριτηριακής ανάλυσης και να στοχεύει στην εφαρμογή μιας συστηματικής, τεκμηριωμένης και τυποποιημένης συλλογιστικής μεθόδου που θα επιτρέπει την ποσοτικοποίηση ποιοτικών κριτηρίων εκτίμησης για την επιλογή, κατάταξη, ταξινόμηση των επενδύσεων.

METHODOLOGY FOR THE EVALUATION & PRIORITIZATION OF INVESTMENTS IN ELECTRICITY DISTRIBUTION NETWORKS AGAINST THE EFFECTS OF CLIMATE CHANGE

Keywords: Climate Change, Electricity Network, Resilience, Adaptation, Investments, Multicriteria Analysis, Criteria Weighting

Abstract

Climate Change and the ever-increasing frequency, intensity, and duration of extreme weather events that occur due to their impacts, is an important factor that affects the entire energy chain, especially the electricity networks. These infrastructures, although they have achieved high degrees of reliability, cannot effectively deal with unpredictable extreme situations that are usually caused by phenomena such as stormy winds, floods, heavy snowfalls, and fires.

Distribution Operators, at an international level, due to the criticality of their role for uninterrupted energy supply to consumers, and as the majority of disturbances have effects at the distribution level, take initiatives and measures to increase the resilience of networks against particularly adverse weather events, but also for their adaptation to Climate Change. System resilience includes its ability to recover rapidly from events and adapt its operation and structure to mitigate their effects on its infrastructure and operation.

In the operation and maintenance activity, investments in specific categories of projects are an important measure, such as the undergrounding of overhead lines, the reconstruction of network elements with more durable materials, the transfer of critical facilities to less vulnerable areas, etc. These investments require significant investment funds with a considerable effect on the consumer's final price many times over. The criteria presented for prioritizing the allocation of funds to projects to improve the resilience of distribution networks and their adaptation to Climate Change are based mainly on the axes of sustainable development, environmental, and social.

This paper examines the factors and individual criteria that must be considered for the prioritization of investments to increase the resilience of networks and the long-term response to Climate Change. At the same time, the methodological decision-making model for the evaluation and prioritization of these investments is analyzed, which is based on the logic of multi-criteria analysis and aims to implement a systematic, documented, and standardized reasoning method that will allow the quantification of qualitative assessment criteria for the selection, ranking, classification of investments.

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ABBREVIATIONS

CDM	Clean Development Mechanism
DSO	Distribution System Operator
EEA	European Environmental Agency
EEA	European Environmental Agency
EPS	Energy Power System
ETS	Emissions Trading
GHG	Greenhouse gases
GSCP	General Secretariat for Civil Protection
HEDNO	Hellenic Electricity Distribution Network Operator
HV	High Voltage
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IPCC	Intergovernmental Panel on Climate Change
IPTO	Independent Power Transmission Operator
JIM	Joint Implementation Mechanism
KTM	Key Type of Measures (EEA)
LV	Low Voltage
NAS	National Adaptation Strategy
NCCAC	National Climate Change Adaptation Committee
NCCAC	National Climate Change Adaptation Committee
NECCA	Natural Environment & Climate Change Agency
NECP	National Energy and Climate Plan
NOA	National Observatory of Athens
NRRR	National Recovery and Resilience Plan
NSACC	National Strategy for Adaptation to Climate Change (Greek Acronym: "ESPKA")
RCP	Representative Concentration Pathway
RCP	Representative Concentration Pathways
RES	Renewable Energy System
RPACC	Regional Plans for Adaptation to Climate Change (Greek Acronym: "PESPKA)
RTU	Remote Terminal Unit
RTU	Remote Terminal Unit
S/S	Substation
SCADA	Supervisory Control and Data Acquisition
SCADA	Supervisory Control and Data Acquisition
SDG	Sustauanble Development Goals
UNFCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

CHAPTER 1
NAVIGATING THE CONCEPT OF CLIMATE CHALLENGE: UNDERSTANDING, ADAPTING, AND TRANSFORMING ENERGY SYSTEMS

1.1 Theoritical Framework – Itroductiry Concepts

1.1.1 Climate Change and the Concept of the Climate Crisis

Climate change, as defined by the United Nations Framework Convention on Climate Change (UNFCC), is a long-term alteration in climate resulting from human activities, distinct from natural climate variability. Human-induced changes, primarily driven by burning fossil fuels like coal, oil, and gas, release greenhouse gases such as carbon dioxide and methane. These emissions create a heat-trapping effect, raising global temperatures. The main sectors contributing to greenhouse gas emissions include energy, industry, transport, buildings, agriculture, and land use. Recognizing climate change's anthropogenic nature is crucial in addressing its impacts and developing strategies for mitigation and adaptation on a global scale.[1]

The Climate Crisis has increased the average temperature of the planet and leads to more frequent extreme conditions of high temperature, such as heatwaves. Higher temperatures can cause increased mortality, reduced productivity and damage to infrastructure.

1.1.2 Extreme Weather Events

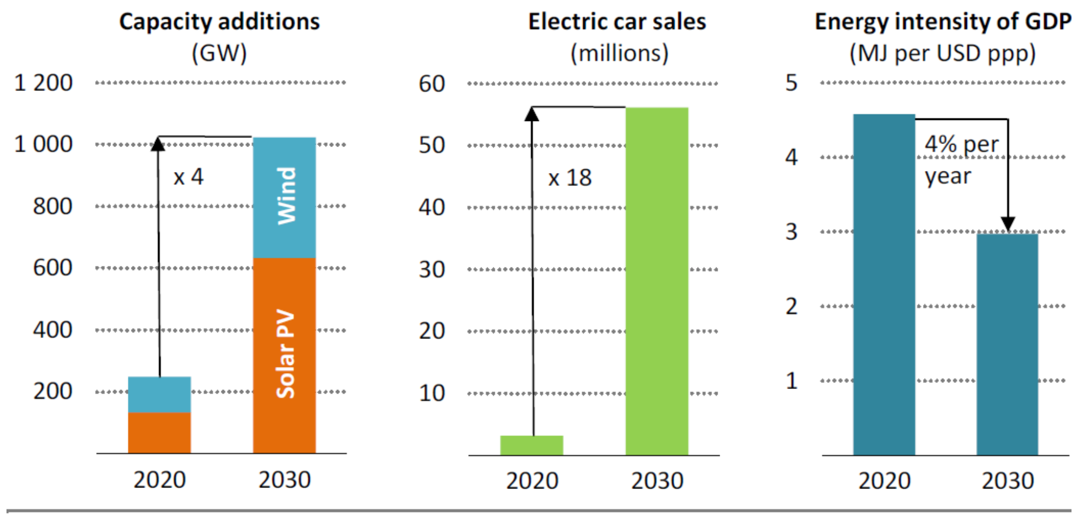
Extreme weather phenomena involve the recording of rare meteorological observations in terms of time, intensity, duration, position, and human damage. Although prediction is possible, the measures required to address such events are deemed costly for continuous maintenance. Dealing with extreme weather falls under the responsibility of specialized emergency coordination services established by countries, often involving various ministries and directorates. These services mobilize personnel and resources when needed. In significant events, international cooperation among emergency coordination services is not uncommon. Examples of extreme weather events include severe storms, particularly the dangerous supercell type, extreme heat waves, hurricanes, and siphons. Managing these phenomena requires coordinated efforts and resources at various levels to mitigate potential impacts.

1.1.3 Lignite phase-out and Clean Energy Technologies

The de-lignitization goal strongly aligns with the EU's commitment to becoming the first climate-neutral continent and is consistent with global energy trends. Utilizing targets and competitive auctions can expedite the transition to renewable energy in the electricity

[1] https://www.un.org/en/climatechange/what-is-climate-change

sector, while phasing out fossil fuels, implementing carbon pricing, and market reforms can ensure fair prices. Policies should discourage specific fuels and technologies like coal-fired power plants, gas boilers, and traditional internal combustion engine vehicles. Governments play a crucial role in spearheading extensive investments in infrastructure, prioritizing "smart" electricity transmission and distribution networks. By promoting these measures, nations can advance their climate objectives and contribute to international efforts for sustainable and low-carbon energy systems.



Note: MJ = megajoules; GDP = gross domestic product in purchasing power parity.

Figure 1: Increase Clean Technologies by 2030 to the Net Zero Path (Source: IEA, 2021a)

1.1.4 The Electricity Power System (EPS)

The traditional form of organization of conventional power plants is based on a centralized approach on the supply side through a centralized structure of energy transmission produced in large power plants (at points where primary energy resources are available) to industrial and domestic users through High Voltage (HV) transmission lines and Medium Voltage (MV) and Low Voltage (LV) distribution lines and has been consolidated thanks to the "economies of scale" it offers.

Despite the excellent coverage of society's energy needs for many years, this energy system needs to be gradually radically transformed throughout the chain in order to meet the data and requirements of the new era driven by the need for the transition from a fossil fuel-based economy to a low-carbon climate-friendly economy, allowing consumers to play an active role by providing them with information and choice and creating flexibility to manage demand and supply. At the same time, the rapid electrification of all sectors makes the role of electricity even more important for energy security around the world.

The energy sector is at the heart of policies to address the adverse effects of climate change and achieve sustainable economic growth, as it is the source of about 75% of greenhouse gas emissions. The goal of decarbonisation by 2050 requires a complete transformation of how energy is produced, transported and consumed, resulting in a clean and resilient energy system. It also requires all governments to significantly strengthen and then successfully and effectively implement their energy and climate policies.[2]

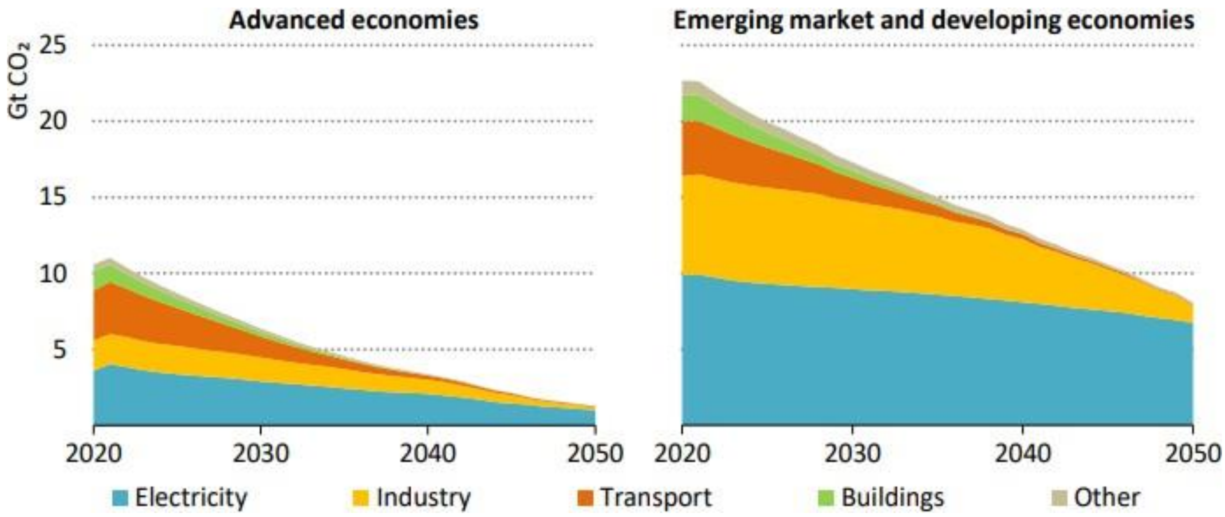


Figure 2: Emissions from existing infrastructure by sector and region (Source: IEA, 2021a)

In particular, the energy transition, based on the triptych **of decarbonization**, **digitalization**, and decentralization, is drastically changing the energy market and leading to tectonic changes in the sector, with the first key change being the production of energy from clean RES. The shift to electrification of the economy will lead to the upgrading of electricity grids with more interconnections and automation, and the development of storage systems with wider benefits for consumers.

As shown in the image below, the key features of future EPS are the following (Chatzivassiliadis, 2009):

- They utilize and use large central stations and distributed generation units with optimal mixing and allow a **bidirectional flow of** electricity.
- They provide electricity to end-users (consumers) **with high reliability**, ensuring and improving security and quality of supply.
- They are **flexible,** meeting the needs of consumers.
- They are characterized by **high penetration of distributed production** and storage units.
- They are **accessible** to network users, allowing their connection at a reasonable cost, especially for RES and cogeneration units.
- They are **economical**, providing the best price through technological innovations and enabling efficient management and competition.
- They are **environmentally friendly**, limiting from the electric sector.
- They are resilient against multiple threats.
- They are governed by a regulatory framework and modern network codes.

[2] Emerging markets and developing economies are responsible for 75% of cumulative emissions from existing infrastructure by 2050

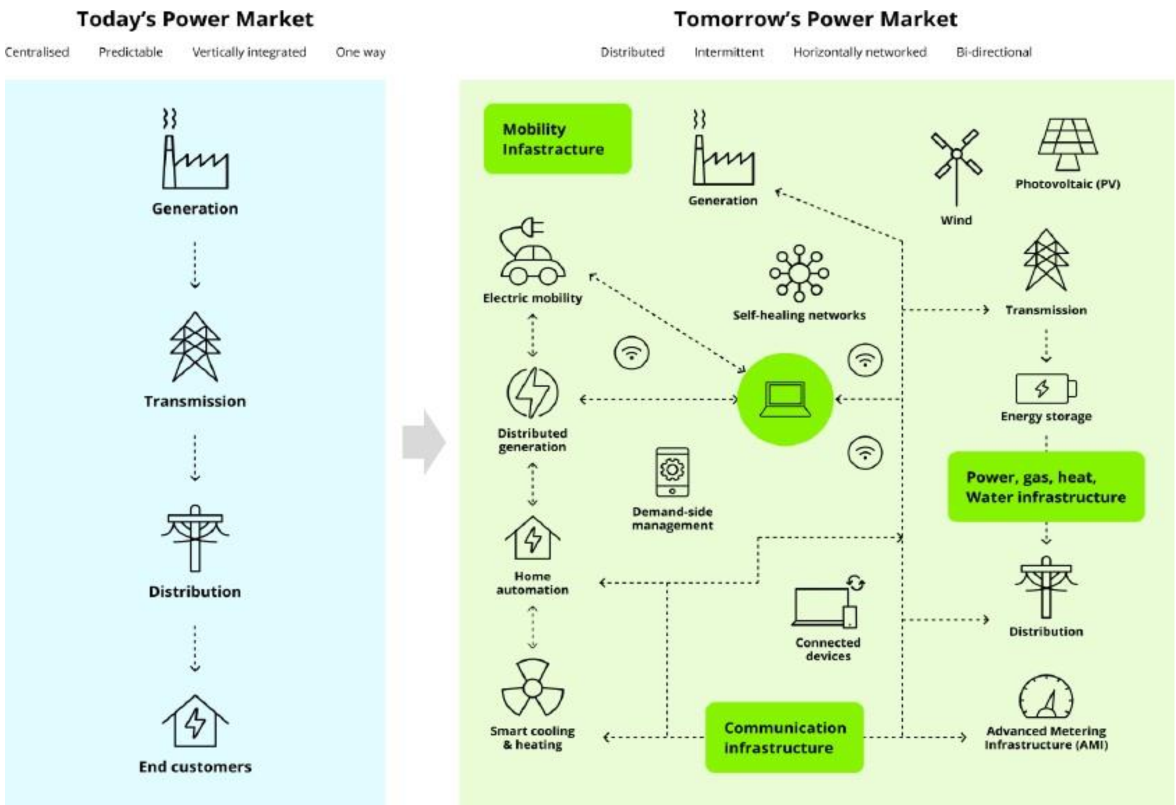


Figure 3: Energy System of the Future using Digital Tools (Source: Deloitte)

The emerging trends that characterize the energy transition to the new modern operating model are presented in detail in the following Chapters.

1.1.5 Smart Grids – Microgrids

Modern EPSs have begun to integrate many digital technologies (Information and Communications Technology - ICT, decentralized intelligence) as well as new electromechanical systems in the activities of electricity production, transmission, distribution, and supply. The electrical networks that achieve the most reliable, cost-effective, sustainable, and safe supply of electricity, utilizing the above technologies in combination with the use of RES and intelligently integrating the actions of all interconnected users-producers, consumers, and those who also two, are characterized as intelligent or intelligent networks (smart grids).

In an ideal "metallignite" era, citizens will have an active role in the production, storage, sale, and general management of clean energy, they will be members of energy communities, they will enjoy the benefits of using smart grids, but also microgrids, obtaining energy independence, in cases of faults in the central network, and achieving cost improvement.

Figure 4: Example of a Smart Grid Illustration (Source: electricaltechnology.org)

Microgrids belonging to smart grids are LV and MV networks that include local RES units, storage devices (batteries) and flexible loads with their operation being subject to constant control.

The main advantage and at the same time characteristic of microgrids is that they can work either interconnected with the grid or autonomously (islanding), providing greater security and reliability in consumption, even in cases where the network faces problems. The operation of microgrids is expected to bring benefits to the overall performance of the system if managed effectively.

Smart meters, as a key pillar of remote metering, are a key factor for monitoring and remote monitoring of the Network, providing rapid access to Distribution Network data, facilitating the monitoring of parameters (frequency, voltage, energy consumption, etc.) and allowing two-way communication to optimize Network management.

Table 1: Differences between Conventional and Smart Grids (Source: Tabrizi, 2021)

Conventional Network	Smart Grid
Electromechanical	Digital (through the use of power electronics and ICT)
One-way flow of electricity (from power stations to consumption centers) One-sided communication	Two-way power generation – Two-way communication and flow of large amounts of information
Centralized Production	Distributed generation
Minimal sensors	Universal use of sensors
Manual monitoring (blind network)	Self-monitoring
Lack of real-time monitoring	Extensive real-time monitoring
Manual control/testing	Remote checks/tests
Breakdowns and blackouts	Adaptability and anticipation
Slow response time	Ultra-fast response time
Manual restoration	Self-medication (automatic detection of routine problems, immediate response and rapid recovery with minimization of downtime)
Limited control	Global control
No energy storage	Energy storage
Minimum customer options	Lots of customer options
Global control by the Administrator	Increased customer involvement

In addition, the installation of smart meters in almost all network users is expected to have significant and multiple benefits to the management of the Network, the operation of the market and the national economy, contributing to the achievement of national targets for energy saving, as smart meters will allow dynamic energy pricing, increase the penetration of RES in the EES (decentralized generation), as well as enhancing the development of new flexibility services (e.g. smart charging).

1.1.6 Renewable Energy Sources (RES)

The climate neutrality roadmap outlines a strategy that combines enhanced energy efficiency, resource optimization, and behavioral changes to counteract the rising demand for energy services amid global economic growth and expanding energy access. The plan emphasizes a shift away from fossil fuels, advocating a significant reliance on renewable energy sources (RES) such as wind, solar, hydroelectric, ocean, geothermal, biomass, and biofuels. This transition, supported by low-carbon generation networks, energy storage, and electricity grids, aims to curtail greenhouse gas emissions, diversify energy sources, and enhance electricity security by reducing dependence on unreliable fossil fuel markets.

While hydropower has historically been a low-emission energy source, the roadmap highlights the pivotal role of wind and solar power in tripling expected RES output by 2030 and increasing it eightfold by 2050, ultimately achieving net zero emissions. The share of renewables in global electricity production is projected to rise from 29% in 2020 to over 60% in 2030 and nearly 90% in 2050. To realize this transition, annual wind and solar capacity additions between 2020-2050 need to be five times higher than the average of the last three years. Two-thirds of the total energy supply in 2050 is expected to come from wind and solar energy, bioenergy, geothermal, and hydropower, with solar energy being the largest contributor, accounting for one-fifth of the energy supply. According to the International Energy Agency (IEA), solar photovoltaic capacity is anticipated to increase twentyfold, and wind power elevenfold by 2050 (IEA, 2021a).

Sector		2020	2030	2050
Electricity sector				
Renewables share in generation		29%	61%	88%
Annual capacity additions (GW):	Total solar PV	134	630	630
	Total wind	114	390	350
	– of which: Offshore wind	5	80	70
	Dispatchable renewables	31	120	90
End-uses sectors				
Renewable share in TFC		5%	12%	19%
Households with rooftop solar PV (million)		25	100	240
Share of solar thermal and geothermal in buildings		2%	5%	12%
Share of solar thermal and geothermal in industry final consumption		0%	1%	2%

Note: TFC = total final consumption.

Figure 5: Key Development Milestones for RES (Source: IEA, 2021a)

Renewables also play an important role in reducing emissions in buildings, industry and transport. In buildings, renewable energy is mainly used to heat water and spaces. In transport, renewables play an important indirect role in reducing emissions through electrification. In addition, they contribute to the immediate reduction of emissions through the use of liquid biofuels and biomethane.

EU legislation promoting renewables has evolved significantly over the past 15 years. In 2009, EU leaders set a target of a 20% share of EU energy consumption coming from renewables by 2020. In 2018, a target of 32% of EU energy consumption coming from renewables was agreed by 2030. In July 2021, in view of the EU's new climate ambitions, a revision of the 40% target by 2030 was proposed to the co-legislators. In parallel, the future post-2030 policy framework is under discussion. With the help of these technologies, customers, industrial and residential, are now able to be both consumers and producers, a role known as a "prosumer".

1.2 International Initiatives to Tackle Climate Change

The scientific community was the first to warn of the dangers as a result of man-made climate change. Based on data from the 1960s and 1970s, significant increases in CO2 concentrations in the atmosphere had been observed, which led first climatologists and then other scientists to press the international community for action. In order to accumulate and enrich scientific knowledge on the greenhouse effect and Climate Change, the Intergovernmental Panel on Climate Change (IPCC) was founded in 1988 under the auspices of the United Nations (UN).

It was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), at the instigation of states participating in the United Nations Conference on the Human Environment, held in Stockholm in 1972.
The main objective of IPCC is to gather and evaluate the scientific knowledge base and research conducted for the study of climate change, the assessment of its consequences, as well as the study of potential policies and actions to address risks and adverse impacts as a result of Climate Change.

The IPCC is an intergovernmental body, open to all member countries of the WMO and UNEP. It shall meet once a year in order to define its internal functioning, principles and work programme or to adopt its reports. It includes three (3) working groups to evaluate the scientific parameters of climate change, its social and economic impacts and the possible policies that can be implemented to address them respectively. The IPCC coordinates scientists from around the world and by 2024 has published a total of six reports (1990, 1995, 2001, 2007, 2014, 2023) on observed climate change and its potential impacts:

- First Assessment Report - FAR in 1990
- Second Assessment Report - SAR in 1995
- Third Assessment Report - TAR in 2001
- AR4 in 2007
- AR5 in 2014
- AR6 in 2023

The IPCC reports are based on scientific publications by expert researchers and contribute substantially to the next international steps towards tackling Climate Change. Indicatively, the first FAR (IPCC, 1990a, 1990b, 1990c) addressed the challenge of Climate Change and the need for international cooperation that led to the **United Nations Framework Convention on Climate Change (UNFCCC**)). The second SAR (IPCC, 1995) led to the adoption of the Kyoto Protocol and the fifth AR5 to the famous Paris Agreement (IPCC, 2014). The sixth AR6 presents guidelines for both short- and long-term responses.

According to the report, the main source of the increase in global warming is the increase in CO2 emissions, stating that it is likely or very likely to exceed 1.5ºC in higher emission scenarios (IPCC, 2021, 2022a, 2022b, 2023). The IPCC has also issued a number of methodological reports (MRs), which provide practical guidelines for the compilation of greenhouse gas inventories for the reporting requirements of UNFCCC Parties.

1.2.1 United Nations Framework Convention on Climate Change (1992)

Having laid the groundwork, the international community, and in particular the members of the United Nations, took a step further in May 1992 towards tackling Climate Change, with the agreement and adoption of the United Nations Framework Convention on Climate Change (UNFCCC). The Framework Convention (UN, 1992) entered into force two (2) years later, on March 21, 1994, and is one of the three (3) parties that make up the Rio Treaty / Earth Summit in Rio de Janeiro. By dividing a total of 186 signatory countries into industrialised and developing countries, the Framework Convention recognises the responsibility of industrialised countries for the bulk of global greenhouse gas emissions and therefore for global warming. It is also recognized that these countries have the institutional and financial capacity to contain them.

The Framework Convention imposes on all contracting parties the obligation to establish national programmes to limit greenhouse gas emissions and to submit regular reports, while requiring industrialized signatory countries, as opposed to developing countries, to achieve stabilisation of their own emissions at 1990 levels by the year 2000. This objective, However, it is not binding. The Parties meet regularly at the **annual meeting/Conference** of the Parties, also known as the Conference of the Parties (COP), which monitors the implementation of the Convention and the obligations of the Parties, as well as an overview of the progress and effectiveness of measures, which is reinforced, where necessary, through new institutional and administrative measures.

1.2.2 Kyoto Protocol (1997)

As early as the first annual meeting (COP 1) held in Berlin in 1995, members deemed it necessary to adopt a Protocol that would be legally binding and aimed at mitigating greenhouse gases from the beginning of the 21st century by the most cost-effective means. In this way, states recognized the deficit of the Framework Convention, which, however, undoubtedly set important goals for tackling Climate Change in the context of international cooperation.

To achieve these goals, the Kyoto Protocol (UN, 1997) was agreed at the third meeting (COP 3) held in December 1997 in the Japanese city of Kyoto, following tough negotiations and divergent views between conflicting interests between developing and developed countries in the international effort to solve the problem of global warming.

The Kyoto Protocol is a "roadmap" outlining the necessary steps to tackle climate change in the long term as a result of rising greenhouse gas emissions. According to it, signatory states commit to reducing their emissions during the first commitment period (2008-2012) by achieving a specific target relative to 1990 (or 1995 emissions for certain gases). In particular, industrialized countries as a whole were forced to cut emissions by an average of 5.2% compared to 1990 levels, while no emission targets were set for developing countries. It should be noted that the five-year commitment horizon (instead of the annual one) was chosen to even out annual fluctuations in emissions due to uncontrollable factors such as weather.

Importantly, it was agreed that the targeting of gas reduction could be achieved through three (3) flexible mechanisms, in order not to harm the global economy, namely:

- **Emissions Trading Scheme - ETS: This mechanism provides for the buying and selling of emission allowances between stakeholders (such as states and obligated installations) according to property rights theory. In particular, this system gave countries that had exceeded the national emission ceiling the right to buy a percentage of gases from countries that had a reserve in it. The reverse was also true, i.e. they could sell gas percentages if they had the opportunity, which also acted as an incentive to reduce them. However, this mechanism had to be carried out under clear rules, otherwise it would lead to complacency on the part of countries.**

- **Joint Implementation Mechanism - JIM: The mechanism enables the implementation of joint programmes and activities between Annex I countries of the Convention, e.g. specific green projects and investments. The parties were allowed to acquire or transfer between themselves Emission Reduction Units depending on the location of projects and offset them against their own emission reduction units in order not to exceed the maximum permissible percentage.**

- **Clean Development Mechanism – CDM: It promoted programmes and projects that supported Appendix II countries in achieving their quantified objectives, but also those that provided financial or technological incentives to non-Annex II countries (mainly developing countries) to contribute to the sustainable and meaningful development set as an objective. Subject to voluntary participation, developed countries benefit from the resulting emission reductions to fulfil part of their obligations, while developing countries benefit from the implementation of programmes (financing, technology, etc.). It is necessary to certify additional emission reductions and existing benefits to address climate change in the developing country.**

Flexible mechanisms are based on the rationale that greenhouse gas emissions are a global problem and that the location where they are reduced is of secondary importance. In this way, reductions can be made where costs are lower, at least in the first phase of the fight against Climate Change. In order for the mechanisms to fulfil their above objectives and to ensure the environmental integrity of the Protocol, There is a need to respect the **principle of complementarity**, i.e. the use of mechanisms should be complementary to national emission reduction actions.

The Kyoto Protocol entered into force and was ratified on 16/02/2005, i.e. eight (8) years after its agreement. However, the global validity of the Protocol and its emergence as a key instrument for reducing global pollutants was mainly hindered by the fact that the USA, the world's largest polluter, decided in 2001 to withdraw and not sign, questioning the scientific validity of the greenhouse effect and considering that its commitment to reducing greenhouse gases would burden its economy. This development was worrying for the fight against the greenhouse effect, as the US alone polluted 36.1% in the 1990 period, compared to the other Annex I countries. Moreover, major polluters such as China, India and Brazil were not bound by the Protocol as developing countries. On the contrary, the EU's stance was very positive, setting an example also to Russia and Australia, which, despite initial disputes, eventually signed the Protocol. As the most ardent supporter of the Protocol, the EU decided to pilot emissions trading within the community before the official launch of the international system and to incorporate the Kyoto Protocol into EU legislation through Directives 2003/87/EC and 2004/101/EC.

1.2.3 United Nations Sustainable Development Goals (2015)

In September 2015, the United Nations Summit adopted the 2030 Agenda for Sustainable Development (the 2030 Agenda - A/RES/70/1). It is an action plan aimed at achieving peace and prosperity, underpinning **17 Sustainable Development Goals (SDGs**).

The 2030 Agenda is the most ambitious global agreement ever reached by the UN, promoting the integration of all three dimensions of sustainable development – social, environmental, and economic – into all sectoral policies while promoting the interconnection and coherence of policy and legislative frameworks related to the Sustainable Development Goals.
Sustainable development can be understood by addressing challenges related to the following **five axes (5 P):**

- People
- Planet
- Prosperity
- Peace
- Partnership

Figure 6: The 17 UN Sustainable Development Goals (SDGs) (Source: United Nations, 2015)

In terms of implementing the SDGs, each of the 17 SDGs is highly ambitious and achieving it by 2030 is challenging. In addition, as it would be difficult to decide how to implement the SDGs and accurately measure progress towards them, each SDG is linked to a number of sub-targets. For the 17 SDGs there are a total of 169 sub-targets reflecting these commitments, while for the implementation of each sub-target there are corresponding indicators to measure its implementation. The UN has established a list of 232 indicators to monitor the SDGs, while the EU has created its own list of 100 indicators. The UN indicator framework was developed by the Inter-agency and Expert Group on Sustainable Development Goal Indicators (IAEG-SDGs).

Among the 17 SDGs, Goal 13 relates to Climate Action and includes sub-targets related to both mitigation and adaptation. In particular, the specific objectives include strengthening the adaptation capacity of all countries to Climate Change, integrating relevant measures into national plans and improving capacities, at human and institutional level, as well as raising awareness on Climate Change issues. At the same time, in the context of the Goals, the need to support developing and least developed countries is stressed, both by implementing the commitment for annual funding of $ 100 billion, and by supporting them in climate change planning and management.

In addition to the overall Climate Action Goal, the 17 SDGs include specific environment-related targets that are significantly related to adaptation:

- **SDG 2** relates to adequate food coverage of the entire population. Climate Change is expected to place a significant burden on the primary sector and the food production value chain in general. Adaptation actions can boost the production of good quality food.

- **SDG 6** is about ensuring access to drinking water for all and its sustainable management through concrete actions to address water scarcity and reduce the number of people affected by water scarcity (e.g. protection and restoration of aquatic ecosystems, implementation of integrated water resources management).
- **SDG 9** refers to the pursuit of building resilient and sustainable infrastructure as well as upgrading and retrofitting existing infrastructure and industries to make them sustainable.
- **SDG 11** outlines the need to make cities and communities sustainable. It includes targets such as reducing the adverse environmental impacts of cities (with a particular focus on air quality and urban and other waste management), universal access to green public spaces, and reducing human and economic losses from natural disasters.
- Finally, **SDGs 14 and 15** address the need to sustainably manage, conserve, and restore marine, coastal and terrestrial ecosystems.

It should be noted, however, that improving the population's resilience to the effects of climate change is indirectly linked to almost all SDGs. For example, adaptation actions in the primary sector of developing economies ensure decent work, economic growth (SDG 8) and less inequalities (SDG 10). In addition, reducing household energy expenditure (heating/cooling) increases disposable income, which can be used in health and/or education services (SDGs 3 and 4).

1.2.4 Paris Agreement (2016)

The Paris Agreement (2016) was signed on 22 April 2016 (Earth Day) and ratified by the EU on 5 October 2016. It is an agreement under the United Nations Framework Convention on Climate Change, which marked a historic milestone in the transition towards climate neutrality by 2050 (this means that pollutants released by polluting production activities must be fully absorbed). In line with this commitment, EU countries agreed that the EU will become the first climate-neutral economy and society by 2050. The long-term objectives of the far-reaching international agreement reached during COP 21 at Le Bourget near Paris, France are to strengthen the global response to the threat of Climate Change in the context of sustainable development (UN, 2015):

- By keeping the increase in global average temperature by 2100 "well below" 2°C above pre-industrial levels and continuing efforts to limit (stabilize) the rise to 1.5°C, recognizing that this will significantly reduce the risks and impacts of Climate Change

- By increasing the capacity of the Parties to adapt to the adverse effects of climate change and strengthening resilience to Climate Change and developing low greenhouse gas emissions, in a way that does not threaten food production

- Making financial flows compatible with the development direction of low greenhouse gas emissions and resilience to Climate Change.

Under the Paris Agreement, each country must define, plan and regularly report on its contribution to tackling global warming through the initiatives it takes. However, no mechanism obliges a country to set a specific emissions target on a specific date, but each target should go beyond the previous ones set. In particular, to achieve the global goal, Parties are required to submit Nationally Determined Contributions (NDCs) to the UNFCCC and implement policies aimed at achieving their stated objectives. The process is dynamic and requires the parties to update their NDCs every five (5) years in a progressive manner in order to reflect the highest possible ambition (principle of progress).

To facilitate the agreed forecast that parties must increase their ambition every five years, the Global Report has been established to assess collective progress, with the first assessment in 2023. The result will be used as input for new nationally determined contributions. Scaling up the ambition of contributions is an important objective of the global stocktake; However, the five-yearly reviews will also assess other factors, such as adaptation, climate finance projections, technology development and transfer.

In December 2020, given the EU's commitment to increase its climate ambition in line with the Paris Agreement, EU leaders adopted a binding EU target of a net domestic reduction in greenhouse gas emissions of at least 55% by 2030 compared to 1990 – significantly more than the EU's previous target of a 40% reduction in emissions by 2030.

1.3 Strategic Framework to Tackle Climate Change

1.3.1 European Union Policy Actions

The climate transition is a key priority for the European Council and the Council of the European Union. Below is an overview of recent EU legislative and policy initiatives on climate.

1.3.2 EU Emissions Trading System (2018)

In February 2018, the EU adopted revised rules for the EU Emissions Trading System (ETS). Established in 2005, the EU ETS is the world's first major carbon market and remains the largest. It caps overall CO2 emissions for heavy industry and power plants.

The total volume of allowable emissions is distributed to companies in the form of permits that can be traded. The revised ETS Directive is an important step towards the EU's 2030 greenhouse gas emission reduction target, as agreed as part of the 2030 Climate and Energy Policy Framework (COM(2014) 15), to meet its commitments under the Paris Agreement. In addition, in December 2019, the EU and Switzerland agreed to link their ETS. This agreement is mutually beneficial for the EU and the Swiss Confederation, as linking schemes to global caps and emissions trading allowances can increase the available emission reduction possibilities and enhance the cost-effectiveness of their trading.

1.3.3 Effort Sharing Regulation (2018)

Greenhouse gas emissions from sectors outside the scope of the EU ETS are regulated by the so-called Effort Sharing Regulation (Regulation (EU) 2018/842), which sets binding targets for annual greenhouse gas emission reductions by Member States for the period between 2021-2030 to help Europe achieve climate neutrality by 2050. The aim of the Regulation is to ensure that sectors These contribute to reducing greenhouse gas emissions. These sectors include buildings, agriculture (non-CO2 emissions), waste management and transport (excluding aviation and international shipping).

1.3.4 European Green Deal (2019)

The launch of the European Green Deal (European Green Deal) in December 2019 (COM(2019) 640) gave new impetus to climate policy and action at EU level. ECA is a new growth strategy to transform the EU into a fair and prosperous society, based on a new economic model for a sustainable and competitive economy, with the aim of achieving climate neutrality by 2050.

A key objective of the ECA is to successfully address interlinked climate and digital challenges, as well as resource efficiency, so that by 2050 there are no net greenhouse gas emissions and economic growth is decoupled from resource use in a circular economy. EPC also aims to protect, conserve and enhance the EU's natural capital, and to ensure the health and well-being of citizens. It consists of eight (8) key policy initiatives with the main ones:
Increasing the EU's climate ambition for 2030 and 2050: Ensuring that all EU policies and all sectors contribute to achieving the climate-neutrality objective.
Supply of clean, affordable and secure energy: Promote further decarbonisation of the energy system, enhance the penetration of renewables with the key role of offshore wind generation, upgrade existing infrastructure and assets for climate resilience and promote innovative technologies such as smart grids, hydrogen grids, carbon capture, storage and use; energy storage, etc.

1.3.5 European Climate Law (2021)

The aim of the European Climate Law (Regulation (EU) 2021/1119), one of the elements of EPC, is to establish a legislative framework to achieve EU climate neutrality by 2050, in line with the scientific findings of the IPCC and the Intergovernmental Science - Policy Platform on Biodiversity and Ecosystem Services (IPBES) as well as to contribute to implementing the Paris Agreement on Climate Change and implementing the SDGs. The legislative proposal also sets out the conditions for setting a trajectory for the EU to reach climate neutrality, regularly assessing progress towards it and the level of ambition of the trajectory set, as well as mechanisms to be activated in case of insufficient progress or inconsistency with the climate-neutrality objective. To ensure that sufficient efforts are made to reduce and prevent emissions by 2030, the climate law sets a limit of €225 million as the contribution of removals to this target. tonnes of CO2 equivalent. The EU will aim to achieve a higher volume of net carbon sinks by 2030. The Regulation establishes a European Scientific Advisory Board on Climate Change to provide independent scientific advice and report on EU measures, climate objectives and indicative budgets for greenhouse gases as well as their consistency with the European Climate Law and the EU's international commitments under the Paris Agreement. In addition, the Legislation provides for the setting of an intermediate climate target for 2040 in the coming years.

1.3.6 Fit for 55% (2021)

In EPC, with the European Climate Law the EU has set itself the binding target of achieving climate neutrality by 2050. This requires current levels of greenhouse gas emissions to be significantly reduced in the coming decades. As an intermediate step towards climate neutrality, the EU has increased its 2030 climate ambition by committing to reducing emissions by at least 55% by 2030 (COM(2021) 550).

In parallel, the EU is working on revising and updating climate, energy and transport legislation with the so-called "Fit for 55" package to align existing law with ambitions for 2030 and 2050.
The package also includes a number of new proposals and initiatives to ensure that EU policies are in line with the objectives agreed by the Council and the European Parliament. The package aims to set out a coherent and balanced framework to achieve the EU's climate objectives and promote the EU's adaptation to the 55% objective, characterised by equity and social fairness, to maintain and strengthen innovation and competitiveness of EU industry, while ensuring a level playing field vis-à-vis third-country economic operators; and support the EU's position as a global leader in the fight against climate change.

EU ministers exchanged views on the proposed package during an informal meeting in Slovenia in July 2021. The EU Forest Strategy for 2030 was presented alongside the package. The Fit for 55 package (COM(2021) 550) includes legislative proposals and policy initiatives (European Commission, 2021a) most importantly:
Social Climate Fund, which will provide dedicated funding to Member States to support European citizens most affected by, or at risk of, energy or mobility poverty in investing in energy efficiency, new heating and cooling systems and cleaner travel, as an accompanying measure to the introduction of emissions trading in road transport and buildings.

1.3.7 EU Strategy on Adaptation to Climate Change (2021)

In June 2021, EU environment ministers adopted conclusions endorsing the new EU strategy on adaptation to climate change.
This strategy, which is a key EPC initiative to achieve the green transformation and sustainable development, outlines a long-term vision to make the EU a climate-resilient society fully adapted to its adverse impacts by 2050.

1.3.8 European Taxonomy for Green Activities (2021)

Regulation (EU) 2020/852 on the EU Taxonomy entered into force in summer 2021, with sustainability disclosure criteria and requirements, aims to create a catalogue of environmentally sustainable economic activities to help the EU increase sustainable investment and implement ECA, providing the necessary tools for investors to identify sustainable investment opportunities. This new classification system is part of wider activity by industry bodies and regulators to build confidence in sustainable finance. The Regulation promotes equal competition and legal certainty for all companies operating within the EU and aims to:

- Redirecting financial capital with a focus on sustainable investments
- Establishing sustainability as a component / pillar of risk management
- Encouraging long-term investment and economic activity

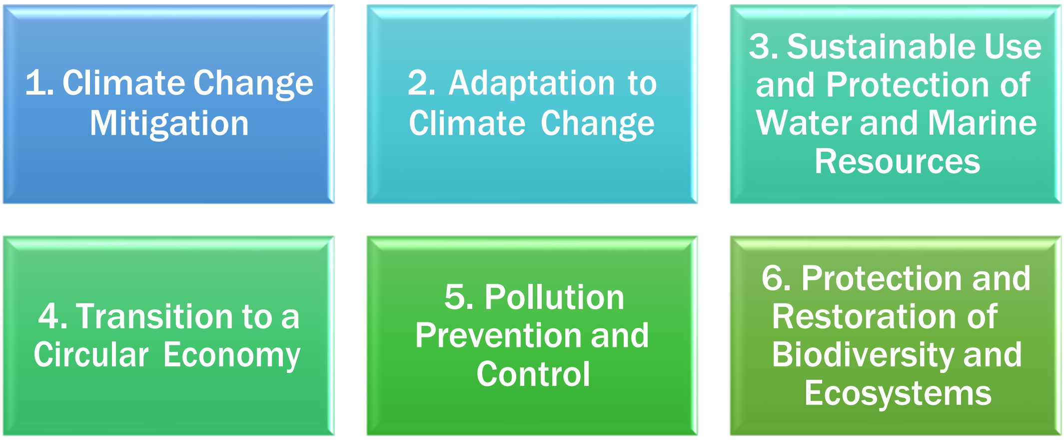


Figure 7: EU Taxonomy priorities (Source: EC)

In this way, the EU Taxonomy can create certainty for investors, help companies become more climate-friendly, mitigate market fragmentation and support the orientation of investments to where they are most needed. Activities that have either a limited carbon footprint or are less vulnerable to the effects of climate change, therefore, are expected to benefit from higher investments.

1.4 Energy Transition and European Energy Policy

1.4.1 Energy Union (2015)

In this context, the EU proceeded with the construction of the Energy Union (COM/2015/080), which was published on 25 February 2015 as a key priority of the Juncker Commission (2014-2019). The objective of a Resilient Energy Union, with an ambitious climate policy at its core, is to provide EU consumers (households and businesses) with secure, sustainable, competitive and affordable energy through an integrated energy system, at continental level, where energy moves freely across borders, based on competition and the best possible use of resources; and effectively regulating energy markets at EU level where needed. Since its launch in 2015, the European Commission has published several packages of measures and regular progress reports monitoring the implementation of this priority to ensure that the Energy Union Strategy is achieved.

The Union's energy strategy has five (5) mutually reinforcing and closely related dimensions (European Commission, 2015) with the main ones:
Climate action and decarbonisation: The EU is committed to ratifying the Paris Agreement, promoting the transition of the European economy to a clean energy system, and maintaining its leadership in renewables.
Research, innovation & competitiveness: Support innovations to address challenges in the context of energy system transformation, such as low CO2 and clean energy technologies, efficient energy systems, etc.

Building the Energy Union was one of the political priorities that put Europe on the right track to become a prosperous, modern, integrated, interconnected, secure, competitive, sustainable and climate neutral economy. The energy transition requires, however, a full economic and social transformation, involving all sectors of the economy and society to achieve the objective of climate neutrality by 2050.

1.4.2 Clean Energy for All Europeans (2019)

The EU energy policy framework was completed in 2019 with the legislative package "Clean Energy for All Europeans", which seeks to facilitate the transition to an energy system that is not dependent on fossil fuels and has limited greenhouse gas emissions (Directive (EU) 2019/944). The package is an important step in implementing the Energy Union strategy and includes, inter alia:

New Regulation on the Governance of the Energy Union and Climate Action (Regulation (EU) 2018/1999) to ensure the achievement of objectives, cooperation of members, long-term predictability of policy, reduction of administrative burdens, etc. Obligation for EU Member States to submit and regularly update National Energy and Climate Plans (NECPs) for the period 2021-2030 presenting their contribution to RES and EE targets. It also requires the development of national strategies for climate neutrality by 2050.

New legislative initiatives in the electricity sector, which will allow the European electricity market to better adapt to the challenges of the transition to a clean energy environment, facilitating the interconnections and integration of renewables. These initiatives rely more on market mechanisms and focus on consumer protection and will help to better protect against unwanted black-outs.

1.4.3 Energy Planning and Climate Goals in Greece

The energy sector contributes approximately €6 billion to the Greek economy, which corresponds to 3.8% of total domestic value added (IOBE, 2021).
The country's energy needs are mainly covered by imports of primary energy (oil and natural gas), and to a lesser extent by domestic production of solid fuels and RES, while the contribution of domestic extraction of crude oil and natural gas is very small.

Transport is the sector with the highest energy consumption, followed by the domestic sector, industry and services. [3]

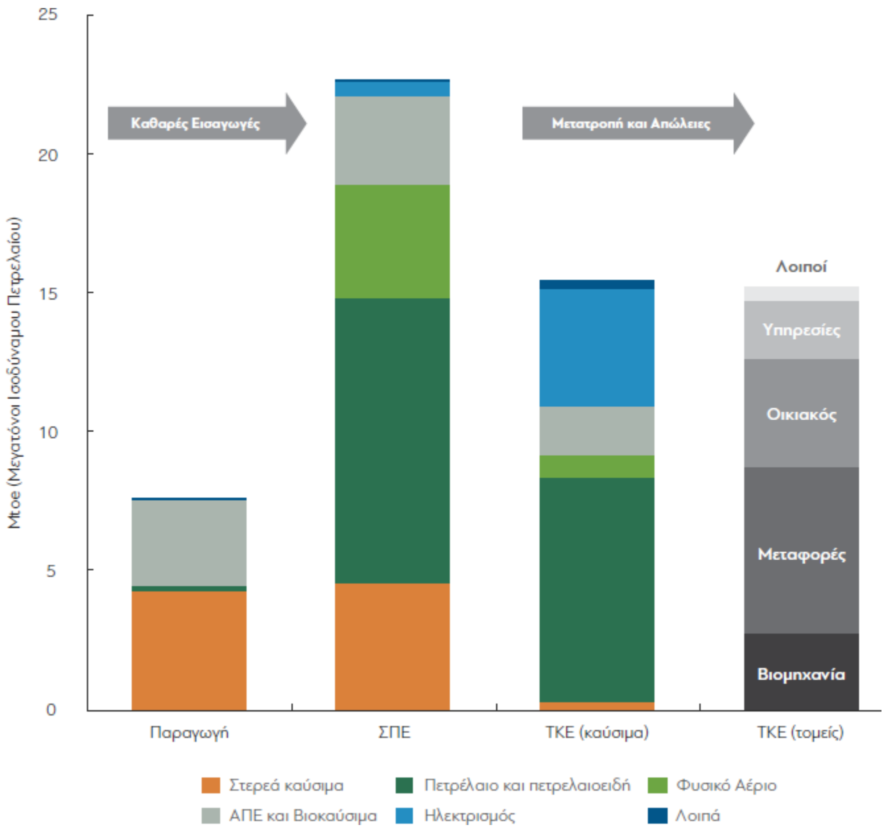


Figure 8: Energy Production and Consumption in Greece in 2018 (Source: Eurostat - IOBE Analysis)

These figures highlight the country's significant energy dependence on energy imports, as well as the fact that Greece remains an economy based on fossil fuels (coal, oil and natural gas), with all that this implies for the size of greenhouse gas emissions. Therefore, drastic reversals are needed to decarbonize the domestic energy system, especially in the transport sector.

However, energy infrastructure in many cases does not meet the requirements that will ensure the transition path towards a low greenhouse gas emission energy system.

[3] ***TES= total energy supply, FEC= final energy consumption.***

Electricity transmission and distribution networks have to deal with saturation issues that will become more pronounced with the further increase in RES penetration. The interconnections of the autonomous island systems with the continental electricity system, despite the progress made in previous years, have not been completed and the losses of electricity in the networks are significant (also due to electricity theft), but are decreasing with the development of decentralized generation. Better utilization of RES and the interruption of electricity production from polluting plants on the islands depend on the completion of these investments. There has also been a relative delay in the development of smart distribution networks and the deployment of smart meters, which should enable consumers to benefit from improved EA and demand response mechanisms while providing flexibility to the EPS.

1.4.4 National Strategy for Adaptation to Climate Change (2016)

Since 2016 and through article 15 of Law 4414/2016, Greece has a National Strategy for Adaptation to Climate Change (Greek Acronym: “ESPKA”), which sets the general objectives and guiding principles for the country's adaptation to Climate Change, per the provisions of the United Nations Framework Convention on Climate Change (article 4), the Paris Agreement (Article 7) and the EU Strategy on Adaptation to Climate Change. The primary purpose of ESPKA is to contribute to strengthening the country's resilience to the effects of Climate Change.

To achieve this goal, ESPKA sets five (5) main objectives:

- Systematizing and improving the decision-making process (short and long-term) related to adaptation to Climate Change.
- Linking adaptation with the promotion of a sustainable development model through regional/local action plans.
- The promotion of adaptation actions and policies in all sectors of the Greek economy, with emphasis on the most vulnerable.
- The creation of a mechanism for monitoring, evaluating, and updating adaptation actions and policies.
- The strengthening of the adaptive capacity of Greek society through information and awareness actions.

The achievement of the individual targets is achieved through the implementation of 13 Regional Plans for Adaptation to Climate Change (Greek Acronym: “PESPKA”). PESPKA proposes the implementation of solutions at the regional level through PESPKAs for the 15 sectors of the Greek economy of higher vulnerability. PESPKA is expected to include an analysis of trends in the main climate parameters in the short, medium (2050), and long term (2100) and for more than one scenario, using existing data and established regional climate models. In addition, they are expected to include vulnerability assessments for specific sectors and/or geographical areas within each region, as well as an assessment of the impacts of climate change on these sectors, which will result in the identification of priority areas and geographical priority areas for action. To date, the development of the 13 PESPKAs has been completed and their formal approval by the Regional Councils is expected to be completed in 2023.

1.4.5 National Energy and Climate Plan (2019)

The National Energy and Climate Plan (NECP) was ratified by No. 4/23.12.2019 Decision of the Government Council for Economic Policy (Government Gazette B' 4893) and constitutes for the Greek Government a Strategic Plan on Climate and Energy issues. The NECP presents a detailed roadmap for achieving specific energy and climate targets by 2030. Specifically, priorities and policy measures are analyzed in a wide range of development and economic activities for the benefit of Greek society, making it a reference document for the next decade. The main policy priorities are:

- Climate change, greenhouse gas emissions and removals
- Renewable energy sources
- Improving energy efficiency
- Security of energy supply
- Energy market
- Research, innovation and competitiveness

In addition, the NECP develops the Long-Term Strategy for the year 2050 on climate and energy issues, in the context of the country's participation in the collective European goal of a successful and sustainable transition to a climate-neutral economy by 2050, at EU level. The Long-Term Strategy has the year 2030 as a reference point and presupposes the achievement of the relevant objectives of the NECP. In 2023, a draft revision of the NECP was proposed in Greece incorporating and outlining measures for strategic priorities such as:

- Rapid development of RES
- Energy storage
- Energy efficiency
- Electrification of light road transport
- Climate-neutral alternative fuels
- Fuel gaseous system
- Bio-economy.
- Creating a green hydrogen economy
- Innovation and systemic solutions in carbon capture and storage for the energy transition of the country's industry (mainly cement production, oil refining, fertilizer manufacturing).
- Support new industries and business activities developing a domestic value chain for green energy transition technologies and energy costs.

Greek National Energy and Climate Plan (NECP): The Greek NECP is a ten-year plan outlining the country's energy and climate targets for 2030. It was enacted in December 2019 and acts as the country's national energy policy in accordance with the Paris Agreement's targets of limiting global temperature rise to 1.5 degrees Celsius and achieving net-zero emissions by 2050. The NECP focuses on energy transition and sets more strict climate and energy targets for 2030 than the EU targets. The key objectives of the Greek NECP are 1) reducing greenhouse gas emissions by over 42% by 2030 compared to 1990 levels, by implementing emission-cutting measures in transport, agriculture, and manufacturing, 2) achieving a minimum 35% share of RES in gross final energy consumption (EU: 32%), with targets of 40% in heating and cooling and 19% in transport, and 3) improving energy efficiency in final energy consumption by 38% (EU: 32.5%) through initiatives to lower it. The NECP also aims to create approximately 100,000 jobs in the clean energy sector by 2030. The Green transition pillar of the Greek NRRP/Greece 2.0 is aligned with many of the NECP's strategic priorities; thus, both have a number of common targets, such as a significant reduction in carbon dioxide emissions by 2030, the deployment of renewable energy sources in the energy mix, and the country's increased energy efficiency and energy security (NECP 2019, Greece 2.0 2021).

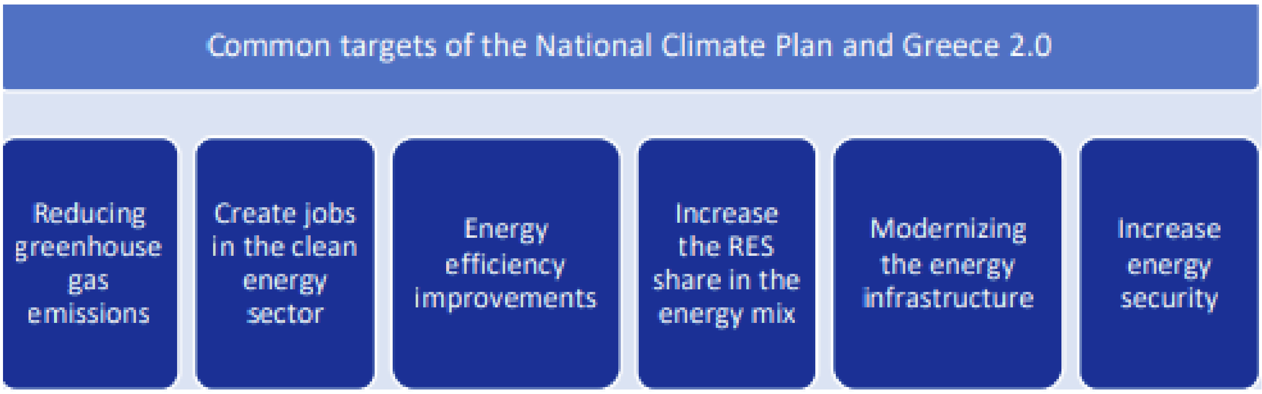


Figure 9: Source: Dr. Kapopoulos E., Dr. Thomaidou F., & Kati S. (2023). Electricity: Renewable Energy Sources and the power landscape in Greece, Alpha Bank - Economic Research Division, alphabankeconomicresearch@alpha.gr

Electricity sector under the NECP: The Greek NECP targets a minimum of 65% renewable energy in electricity generation and 60% in electricity consumption by 2030. To meet this ambitious goal, the NECP includes initiatives such as streamlining and expediting the approval process for RES generating plants, integrating RES into the power system, operating energy storage systems, and promoting electromobility. In addition to the RES target, the NECP aims to phase out the use of lignite in electricity production and close all lignite-fired power stations by 2028.

Ending lignite use would be a significant step forward for Greece's attempts to combat climate change. To address the energy crisis, the Greek government has chosen to extend the operation of seven lignite-fired power plants to the end of 2025, raising concerns about Greece's commitment to climate action (NECP 2019, Greece 2.0 2021, www.kathimerini.gr).

1.4.6 National Recovery and Resilience Plan (2021)

The National Recovery and Resilience Plan (NRRP) "Greece 2.0" was approved on 13 July 2021 by the Economic and Financial Affairs Council configuration (Ecofin). It includes 106 investments and 68 reforms, raising €31.16 billion, of which €30.5 billion in European funds. (€18.43 billion in aid and €12.73 billion in loans) to mobilise €60 billion in total investment in the country over the next five years. The NRRP consists of four (4) pillars:

- Green Transition,
- Digital Transformation,
- employment, skills, social cohesion,
- Private Investment and Economic Transformation.

In the NRRP, the energy investments that have been included for funding by the Recovery Fund in order to promote the green transition are the following:
Underground and upgrading of the Electricity Distribution Network in urban areas to shield against extreme weather events. It will concern settlements of particular cultural or tourist value and cities with priority in areas where the Network is vulnerable to weather phenomena in order to improve its resilience.

Upgrading of the Electricity Distribution Network in forest areas to prevent fires, including the replacement of bare MT overhead cables, underground or relocation of the Network in forest areas, and installation of insulating covers on Network elements. The aim is to enhance the reliability of the grid (Energy Quality Indicators: System Average Interruption Duration Index – SAIDI and System Average Interruption Frequency Index – SAIFI) and the protection of forest areas.
Increase of the power of electricity distribution substations to facilitate the connection of new RES. Increase of installed capacity in existing HV/MV Substations (addition of new power transformers or replacement of existing ones with larger ones), to remove technical restrictions for connecting new RES units.
Despite the shortcomings identified (IENE, 2021), the NRRP is an extremely useful, forward-looking, and ambitious development plan. However, it is particularly demanding in its implementation, which requires political will, respect for national & European rules, transparency, determination, and commitment to goals. In addition, planned investments and reforms need to be converted into projects, following specific budgets and time milestones.

1.4.7 National Climate Law (2022)

The country's roadmap towards climate neutrality by 2050 is included in the National Climate Law 4936/2022 (Government Gazette A 105/27.5.2022 – Transition to climate neutrality and adaptation to climate change, urgent provisions to address the energy crisis and protect the environment), which lays the foundations for the penetration of green energy and defines the institutional framework for the gradual reduction of anthropogenic greenhouse gas emissions to all productive sectors, while creating a framework for the active participation of citizens in the effort to tackle the climate crisis. The National Climate Law includes:

- National quantitative targets and their allocation to the 7 main sectors (electricity and heat generation, transport, industry, buildings, agriculture and livestock, waste, land use – land use change – forestry) through the preparation of five-year carbon budgets based on NECP projections. Specifically:
- Reduce greenhouse gas emissions by 55% by 2030 and by 80% by 2040 compared to 1990.
- Climate neutrality by 2050

Integration of climate change adaptation measures into sectoral policies. In particular, to take appropriate measures and implement actions that will ensure the creation of a climate-resilient society, the following are established:

- National Strategy for Adaptation to Climate Change (Greek Acronym "ESPKA") covering at least 10 years and revised every five years. The APSC sets out the strategic framework with a view to establishing guidelines.
- Regional Plans for Adaptation to Climate Change (PESPKA). PESPA are prepared by the Regions, identify and prioritize the necessary adaptation measures and actions at a regional level, cover 7 years, and are evaluated every five years.
- National Observatory for Adaptation to Climate Change, which is an open network for the exchange of information and information. The National Observatory for Adaptation to Climate Change in collaboration with the National Meteorological Service (NMS), the National Observatory, and other research, academic and public bodies, is developing a single national climate database, which includes the development and operation of a National Information Web Hub on Adaptation to Climate Change and is constantly updated to provide reliable forecasts and other relevant climate data services.
- Climate Dialogue Forum with representatives of local authorities of the first and second degree, universities, environmental non-governmental organizations, and other bodies.
- Five-year sectoral carbon budgets in specific sectors (electricity and heat generation, transport, industry, buildings, agriculture and livestock, etc.), accompanied by implementing regulations specifying the measures, lines of action and orientations of the NECP.
- Governance system through the establishment of specific bodies responsible for coordinating and monitoring measures to tackle the climate crisis, as well as monitoring indicators
- General guidelines and specific measures, as indicatively mentioned:
- Discontinuation of electricity production from solid fossil fuels until 31/12/2028
- Elaboration of Municipal Plans for the Reduction of Carbon Dioxide Emissions by Municipalities from 2023
- Redefinition of the content of Environmental Impact Assessment (EIA) files, to adapt them to climate change.
- Measures to promote the circulation of very low or zero-emission vehicles
- Arrangements to enhance electromobility by ensuring the adequacy and installation of publicly accessible electric vehicle (EV) recharging points
- Measures for buildings
- Measures to reduce emissions from businesses
- Reduction of emissions in Non-Interconnected Islands (NIIs) through the establishment of a Development Strategic Framework ("GR-eco islands") aiming at their integrated transition towards climate neutrality
- Adaptation measures to the climate crisis, such as mandatory risk insurance for new buildings in zones of high vulnerability based on Regional plans
- Financial incentives

CHAPTER 2
ENERGIZING SUSTAINABILITY: ASSESSING TRENDS, VULNERABILITIES, AND RESILIENCE IN GREECE'S ENERGY SECTOR AMID CLIMATE CHANGE

2.1 Representative Concentration Pathways

According to the Swiss Re Institute's Research Report "The Economics of Climate Change: No Action Not an Option" published in 2021, if the 2050 net-zero emissions and Paris Agreement climate change targets are not realized, the global economy might shrink by 10%. Specifically, if current trends continue, global GDP might be 11-14% lower by mid-century than in a world without climate change. The loss under the Paris Agreement targets would be substantially lower (about 4%). Suppose climate change continues on its current course and the Paris Agreement and 2050 net-zero emissions targets are not fulfilled. In that case, the world's total economic value will be reduced by over 10% by midcentury. Many emerging markets stand to benefit the most if the globe can keep rising temperatures under control. For example, taking action today to return to the Paris temperature rise scenario would mean that southeast Asian economies might avoid losing around a quarter of their GDP by mid-century. Their methodology in this report is novel in that it explicitly accounts for the many uncertainties surrounding the effects of climate change. It demonstrates that the economies most sensitive to the potential physical risks of climate change will profit the most from keeping temperature rises under control. This comprises some of the world's most active rising economies, which are expected to drive global growth in the coming years. The analysis sends a clear message: taking no action on climate change is not an option.

A recent scientific study indicates that current projected temperature rise trajectories, if mitigation promises are implemented, will result in global warming of 2.0-2.6°C by mid-century. We utilize this as a baseline to estimate the impact of rising temperatures over time, while also accounting for the uncertainties around the most severe physical impacts. As a result, global GDP would be 11-14% lower than in a world without climate change (0°C change). Under the same no-climate-change comparison, the Paris aim has a negative GDP impact, albeit less severely (-4.2%). It also investigates a severe scenario in which temperatures rise by 3.2°C by mid-century with no action taken by society to mitigate climate change. In this scenario, the global economy would be 18% smaller than in a world without warming, emphasizing the need for even more action on climate change.

Climate change creates transition risks in addition to physical risks. As the world transitions to a low-carbon economy, they might manifest as significant swings in asset prices and greater business expenses. In a second exercise, they utilized carbon-tax scenario analysis as a proxy to estimate the financial and economic consequences. It was discovered that earnings in the utilities, materials, and energy sectors would be the most impacted, losing 40-80% of earnings per share if a worldwide carbon tax of USD 100 per metric ton were imposed immediately. Revenue-weighted earnings would fall by nearly a fifth in Asia Pacific and 15% in the Americas and Europe, respectively. The magnitude of the loss is determined by the rate at which carbon taxes and mitigation measures are implemented, as well as the rate of technological adoption.

The IPCC's Representative Concentration Pathways display several GHG concentration trajectories and corresponding global temperature rise ranges. The Intergovernmental Panel on Climate Change (IPCC) created a range of "Representative Concentration Pathway" (RCP) scenarios in its Fifth Assessment Report (AR 5) in 2014 to predict GHG emissions and atmospheric concentrations. Climate change mitigation activities under RCP 2.6 would limit average global temperature rise to less than 2°C over pre-industrial levels by 2100. Global temperatures climb by more than 4°C by 2100 in the extreme "business-as-usual" RCP 8.5 scenario, in which no attempts to reduce GHG emissions are done.

Representative Concentration Pathway scenario descriptions

Pathway	Scenario description
RCP 2.6	Under RCP 2.6, carbon concentration delivers radiative forces at an average of 2.6 watts per square meter (W/m2). According to the IPCC, under "a very stringent" RCP 2.6 pathway, average global temperature rise will remain below 2°C by 2100. This is the Paris Agreement's long-term target, alongside an "aspirational" goal of a limit of a 1.5°C increase.
RCP 4.5	The IPCC says RCP 4.5 is an intermediate scenario. Emissions in the atmosphere peak at around 2040 and then decline. Under the RCP 4.5 pathway, global temperatures will rise by between 1.7–3.2°C by 2100. For mid-century (2046–2065) this means a likely range of 1.5–2.6°C warming.
RCP 6.0	In RCP 6.0, emissions peak around 2080 and then decline. In this scenario, global temperatures will rise by between 2.0–3.7°C between the years 2081–2100 from pre-industrial times.
RCP 8.5	This pathway assumes no action is taken to reduce GHG emissions. In this scenario, according to the IPCC, global temperatures will rise by between 3.2–5.4°C between the years 2081–2100 from pre-industrial times. For mid-cenury, the likely range is 2.0–3.2°C warming. Our severe scenario assumes the higher end of 3.2°C warming by mid-century.

Source: IPCC, Swiss Re Institute

Figure 10: IPCC's Representative Concentration Pathways scenario descriptions

Recent models indicate that the climate sensitivity to GHG emissions may be greater than that reported in the RCPs.

To simulate climate evolution, climate models are used for different greenhouse gas concentration scenarios (RCP – Representative Concentration Pathways). These scenarios, developed by the IPCC, describe four different 21st century pathways, i.e., four different climate futures, all of which are considered possible depending on the volume of greenhouse gases (GHG) emitted in the years to come. Each scenario is characterised by a change in net radiation at the top of the troposphere up to year 2100, with respect to the corresponding value for the pre-industrial era, expressed in W/m2 (e.g. the change in net radiation in 2100 for RCP 8.5 is 8.5 W/m2). RCPs represent the range of greenhouse gas emissions covered in the wider literature and include a strict mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and a scenario with very high greenhouse gas emissions (RCP8.5).

The Mediterranean region is often considered as a climate-change hotspot because, in addition to rising temperatures, it will also get drier. In Greece, by the end of the 21st century the temperature is predicted to rise significantly, between 1.07-3.02 °C in a moderate warming scenario (RCP 4.5) and 3.6-5.6 °C in a high warming scenario (RCP 8.5).

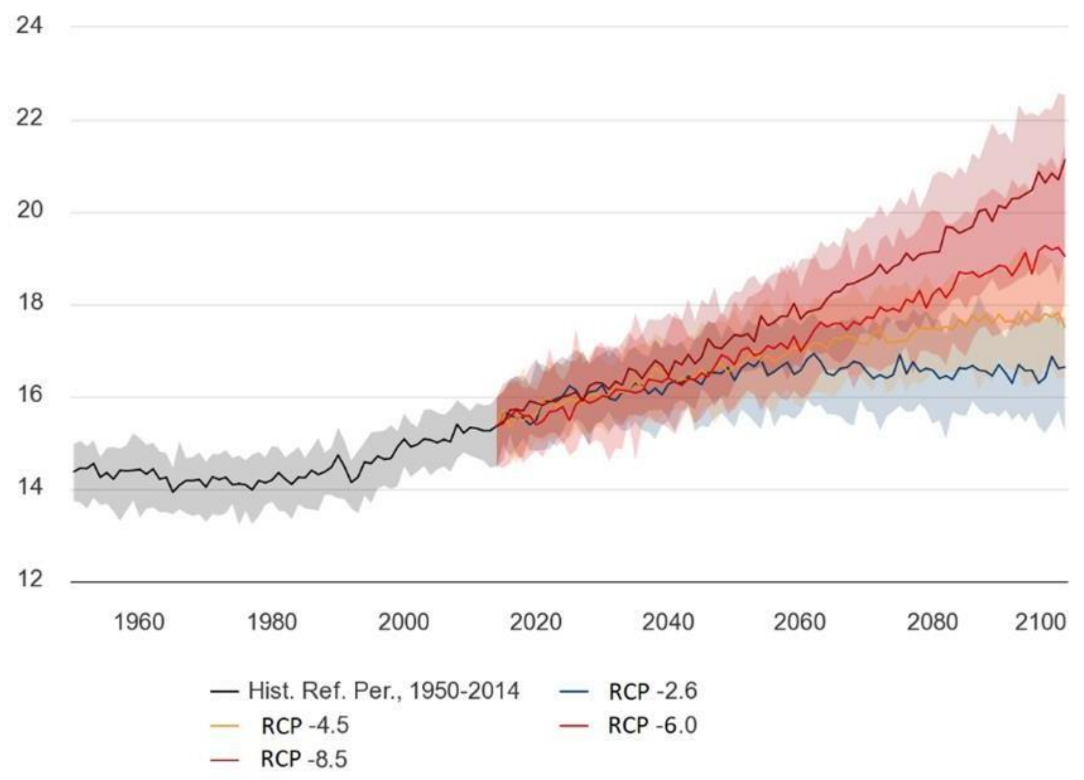


Figure 11: Climate Projection for the average surface air temperature in Greece (ref. period 1995-2014[4])

Additionally, the number of heat waves that will be experienced until 2050 are projected to increase drastically at a national level (**Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**). In the worst-case scenario (RCP 8.5) presented by the IPCC, Greece might experience, by mid-century, at least four additional annual heatwave episodes, with parts of southern Greece going through eight additional episodes.

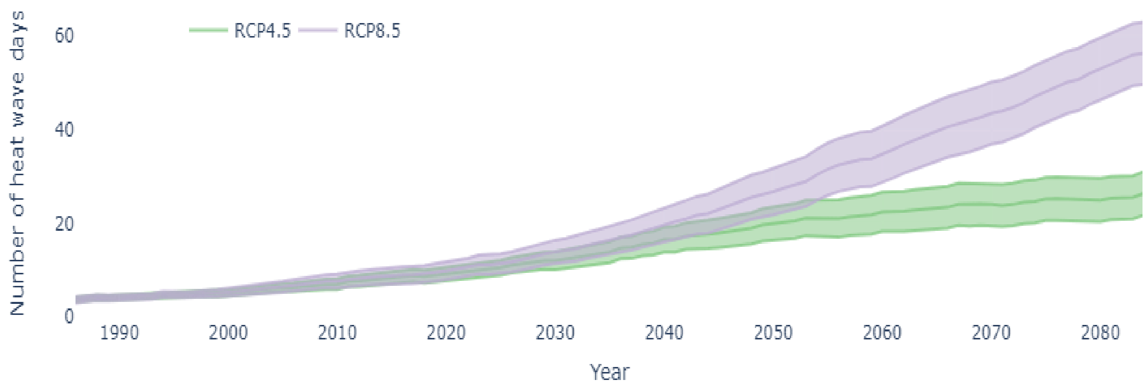


Figure 12: Number of heat wave days per year in Greece[5]

[4] Climate Change Knowledge Portal, World Bank Group

[5] https://cds.climate.copernicus.eu/cdsapp#!/software/app-health-urban-heat-related-mortality-projections?tab=app

Table 2: Overview of climate-related hazards in Greece, according to the Classification of Annex A of regulation (EU) 2020/852 (Taxonomy Regulation), along with an indication of expected future change [6]

	Temperature related	Wind related	Water related	Solid mass related
Chronic	Changing temperature (↑)	Changing wind patterns (0)	Changing precipitation patterns and types (?)	Coastal erosion (↑)
	Temperature variability (↑)		Precipitation and/or hydrological variability (↑)	Soil degradation (including desertification) (↑)
	Permafrost thawing (0)		Ocean acidification (0)	Soil erosion (↑)
			Saline intrusion (↑)	Solifluction (0)
			Sea level rise (↑)	
			Change in sea ice cover (0)	
			Water scarcity (↑)	
Acute	Heat wave (↑)	Cyclone (?)	Drought (↑)	Avalanche (0)
	Cold wave/frost (↓)	Storm (?)	Heavy precipitation (?)	Landslide (↑)
	Wildfire (↑)	Tornado (0)	Flood (coastal, fluvial, pluvial, ground water, flash) (↑)	Subsidence (0)
			Snow and ice load (↓)	
			Glacial lake outburst (0)	

Legend:

Current situation: Green: observed / Red: NOT observed.

Qualitative indication of change compared to the observed situation:

↑: significantly increasing (in frequency and/or magnitude) or becoming significant in future while not necessarily constituting a climate hazard

↓: significantly decreasing (in frequency and/or magnitude)

?: with an uncertain or unknown evolution, where possible referring to the time horizon indicated in the previous field, e.g. due to different results from different models, to different geographical areas or because the hazard is mentioned in the climate risk assessment but an in-depth assessment is not yet available

0: hazard not of relevance, for hazards that are also not significant as observed climate hazards. This is the standard value filled in for all future hazards (e.g., to avoid negative reporting about sea level rise by landlocked countries)

[6] The table has been created using data submitted by Greece to the European Commission in the context of its obligation to report progress on "National Climate Change Adaptation Planning and Strategies", as required by article 19 par. 1 of the Regulation on the Governance of the Energy Union and Climate Action (EU) 2018/1999

2.2 Climate Economics Index: a measure of overall country vulnerability in assessing the economic implications of climate change.

Losses from extreme weather and other natural disasters have been increasing: The climate risk scores measure the likelihood of severe weather events. However, the ratings do not show the economic impact of those events as a pure hazard measure. The relationship between GHG emissions and natural disaster occurrence is not fully understood, but there is emerging evidence that, because of climate change, an increase in the frequency and intensity of secondary danger disaster events has contributed to an increase in consequent losses over the previous decade. Furthermore, increased loss totals from extreme weather events are the result of more people moving to risky areas, notably coastal areas, and as economic assets accumulate. This is one of our approach's shortcomings. They are now unable to properly map specific economic outputs and developments throughout all regions of the world, which may subsequently be linked with climate risk scores due to methodological limits.[7] **The Swiss Re Institute created the Climate Economics Index to assess countries' sensitivity to the overall physical hazards posed by climate change:**

They bring together the economic sensitivity of countries to both the chronic hazards associated with global temperature rises and the acute risks that severe weather events present as a third phase in their assessment of the total physical effects of climate change. Their team initially calculated the GDP impact by analyzing climate scenarios. Second, they assessed country-specific vulnerabilities to extreme weather occurrences (climate risk ratings), which were aggregated to national averages depending on geographical location. Although the country-level aggregate does not fully reflect the complexity of the underlying climate risk scores at individual sites, the averaging of score values provide a riskiness evaluation that is comparable across countries of varying sizes.

Finally, based on countries' existing levels of adaptation capacity, they provided an assessment of the degree of preparedness to deal with the implications of negative climate change impacts. These three measures are used to provide the Climate Economics Index rankings:

[7] See Climate risk and response: Physical hazards and socioeconomic impacts, McKinsey Global Institute, January 2020.

Step 3: Climate Economics Index – construction

- We use a simple ranking method to build an aggregate Climate Economics Index. This index captures the economic impact estimates, our climate risk scores of exposure to severe weather events across geographies, and countries' current adaptive capacity to climate change.

- We assign a 70% index weight to the physical risk space, divided between chronic and acute risks. While this weight is arbitrary, we view physical risk as the driving factor of economic outcomes globally. In addition, country rankings are robust to different weighting approaches.

- Based on results of the economic scenario analysis, the chronic risk index (30% of overall index) ranks countries by size of aggregate negative GDP-impact from climate change, subject to a parameter uncertainty stress-test multiple of x10 (as in Table 2). [24] We use the percentage loss of GDP to proxy for the relative riskiness of different countries to adverse economic outcomes of climate change. The GDP impact is least severe in Denmark (GDP -2.8% by mid-century, rank 1) and most severe in Malaysia (GDP -36.3%, rank 48).

- As revealed in the country-aggregated climate risk scores, the category for exposure to severe weather events (acute physical risks, 40% of overall index) is broken down further. We assign a 50:50 weighting to each of the dry and wet CRS scores for each country (20% of total index each). We rank the dry and wet scores from lowest (1) to highest (48).

- Lastly, our index also includes a proxy to measure a country's current capacity to cope with the negative impact from climate change: the "Climate Change Adaptive Capacity" index from Verisk Maplecroft. This is a composite index with multiple input factors including strength of existing institutional set-up (eg, government stability, presence of a national disaster management ministry, agency or body), level of education and innovation, management of resources (eg. average dietary supply adequacy, pressure from future population growth), degree of reliance on a vulnerable economy (ie, agriculture value added as a percentage of GDP), public awareness, and scope of existing finances and burdens (mainly measured through GDP per capita). We assign it a 30% weight in the total index, and rank countries from strongest (Germany, 1) to weakest adaptive capacity (Venezuela, 48).

Figure 13: Source: Jessie Guo, Daniel Kubli, & Patrick Saner. (2021). The Economics of Climate Change: No Action not an Option., Swiss Re Institute, institute@swissre.com

Climate Economics Index: mid-of-century

Rank	Country	Physical risk (70%)			Current adaptive capacity (30%)	Climate Economics Index
		Chronic risk (GDP impact) (30%)	Acute risk (extreme weather risk)			
			Dry climate risk score (20%)	Wet climate risk score (20%)		
1	Finland	3	8	32	8	11.3
2	Switzerland	4	12	37	2	11.6
3	Austria	7	15	41	6	15.1
4	Portugal	9	21	30	10	15.9
5	Canada	12	18	20	16	16.0
6	Norway	6	29	34	10	17.4
7	US	13	34	12	16	17.9
8	Sweden	10	28	36	7	17.9
9	Denmark	1	40	48	3	18.8
10	Germany	17	25	45	1	19.4
11	Japan	22	35	16	9	19.5
12	Spain	14	17	31	19	19.5
13	Greece	28	3	25	21	20.3
14	Australia	33	16	17	13	20.4
15	UK	11	38	47	4	21.1
16	Turkey	15	4	26	36	21.3
17	Netherlands	5	26	46	18	21.3
18	New Zealand	29	2	27	24	21.7
19	Italy	31	7	33	15	21.8
20	Korea	24	30	14	20	22.0
21	Hungary	19	9	39	23	22.2
22	UAE	21	5	35	27	22.4
23	Hong Kong	41	6	1	29	22.4
24	Romania	8	27	42	21	22.5
25	Belgium	35	39	2	13	22.6
26	Ukraine	2	10	38	42	22.8
27	France	26	19	40	12	23.2
28	Argentina	20	22	10	37	23.5
29	Mexico	25	20	15	31	23.8
30	Egypt	23	11	3	47	23.8
31	Russia	27	13	28	32	25.9
32	Poland	16	24	44	25	25.9
33	Czech	18	23	43	26	26.4
34	Saudi Arabia	43	14	4	38	27.9
35	South Africa	37	1	18	45	28.4
36	Chile	39	31	9	30	28.7
37	Taiwan	40	41	6	28	29.8
38	Brazil	34	42	8	33	30.1
39	Singapore	47	44	29	5	30.2
40	Peru	30	46	7	41	31.9
41	China	38	33	21	35	32.7
42	Colombia	36	38	22	40	34.8
43	Venezuela	32	32	24	48	35.2
44	Thailand	45	43	11	39	36.0
45	India	42	37	13	46	36.4
46	Philippines	46	48	5	43	37.3
47	Malaysia	48	47	23	33	38.3
48	Indonesia	44	45	19	44	39.2

Figure 14: Source: Jessie Guo, Daniel Kubli, & Patrick Saner. (2021). The Economics of Climate Change: No Action not an Option., Swiss Re Institute, institute@swissre.com

Some advanced economies rank higher on the Climate Economics Index, which reflects their current levels of adaptability.

Lower-income countries are the most vulnerable: Many of the industrialized economies' vast economies are well-positioned to resist the harmful effects of climate change. Canada, the United States, and Germany, for example, all rank among the top ten in terms of climate resilience. They are all located at higher latitudes, implying that rising temperatures will have less of an impact on productivity. They have a stronger mitigation infrastructure as well. China and India are both ranked quite low (41 and 45, in the above table respectively). This underscores the large GDP impact loss estimated in our scenario study (China, GDP -18.1% by mid-century; India, GDP -27%, as shown in the table below) as well as low levels of adaptive capacity to date. The 30% weighting given to the Maplecroft index for existing adaptive capacities is crucial in the case of China. As a leader in green energy projects, and with increased awareness of climate risk (as indicated by the emphasis on green transformation mandated in China's newest 14th five-year plan), we anticipate China will rise and place significantly higher in the index rankings in the next years.

The countries most adversely affected are frequently the ones least prepared to minimize the effects of climate change: According to the index rankings, climate change has a greater negative impact on developing countries with lower per capita income. Southeast Asia, Latin America, the Middle East, and Africa, for example, score low in terms of aggregate physical risk and adaptability capacity. Singapore is an exception. Though not a growing economy, being a small island city-state, it is very vulnerable to a variety of physical threats (for example, sea level rise and heat stress). At the same time, it possesses a high level of adaptive potential to counteract the negative effects of climate change. Overall, Singapore is more resilient to the effects of global warming than its ASEAN counterparts. Improving the capacity of the most vulnerable countries to mitigate economic damage will boost long-term prosperity. This is significant because climate change risks might have a negative impact on sovereign credit ratings. It reveals a vital and potentially hazardous financial feedback loop for the most vulnerable countries, both physically and economically. Building solid infrastructure and institutions can help to mitigate GDP losses from disasters and promote rapid recovery after the occurrence.

Mid-century GDP changes with different temperature rises and economic impact severity, relative to a no-climate change world

Temperature path	Well below 2°C increase			2.0°C increase			2.6°C increase			3.2°C increase		
	Paris target			*The likely range of global temperature gains*						*Severe case*		
Omitted channels	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(Un)known unknowns	✗	✓x5	✓x10	✗	✓x5	✓x10	✗	✓x5	✓x10	✗	✓x5	✓x10
World	−0.5%	−2.2%	−4.2%	−1.3%	−5.7%	−11.0%	−1.7%	−7.2%	−13.9%	−2.2%	−9.4%	−18.1%
OECD	−0.4%	−1.6%	−3.1%	−0.8%	−3.9%	−7.6%	−0.9%	−4.1%	−8.1%	−1.1%	−5.4%	−10.6%
North America	−0.5%	−1.7%	−3.1%	−0.9%	−3.7%	−6.9%	−1.0%	−4.0%	−7.4%	−1.2%	−5.1%	−9.5%
South America	−0.4%	−2.0%	−4.1%	−1.1%	−5.5%	−10.8%	−1.4%	−6.6%	−13.0%	−1.8%	−8.6%	−17.0%
Europe	−0.2%	−1.4%	−2.8%	−0.7%	−3.8%	−7.7%	−0.8%	−4.0%	−8.0%	−1.0%	−5.2%	−10.5%
Middle East & Africa	−0.7%	−2.5%	−4.7%	−2.4%	−7.6%	−14.0%	−4.6%	−12.1%	−21.5%	−5.2%	−15.0%	−27.6%
Asia	−0.7%	−2.8%	−5.5%	−1.7%	−7.7%	−14.9%	−2.4%	−10.5%	−20.4%	−3.0%	−13.7%	−26.5%
Advanced Asia	−0.4%	−1.7%	−3.3%	−1.1%	−4.8%	−9.5%	−1.3%	−5.9%	−11.7%	−1.7%	−7.7%	−15.4%
ASEAN	−0.8%	−2.3%	−4.2%	−2.4%	−9.0%	−17.0%	−4.1%	−15.4%	−29.0%	−5.0%	−19.7%	−37.4%
Oceania	−0.5%	−2.2%	−4.3%	−1.3%	−5.8%	−11.2%	−1.7%	−6.5%	−12.3%	−2.0%	−8.3%	−16.3%
Argentina	−0.4%	−1.6%	−3.1%	−0.8%	−3.9%	−7.7%	−0.9%	−4.3%	−8.6%	−1.2%	−5.7%	−11.3%
Australia	−0.5%	−2.2%	−4.4%	−1.4%	−5.8%	−11.3%	−1.7%	−6.6%	−12.5%	−2.1%	−8.4%	−16.5%
Austria	0.1%	−0.8%	−2.0%	0.0%	−2.6%	−5.9%	0.4%	−2.3%	−5.7%	0.2%	−3.3%	−7.9%
Belgium	−0.1%	−1.2%	−2.5%	−0.4%	−3.0%	−6.4%	−0.2%	−2.9%	−6.3%	−0.4%	−4.0%	−8.5%
Brazil	−0.4%	−1.9%	−3.7%	−1.0%	−5.1%	−10.3%	−1.2%	−6.3%	−12.8%	−1.6%	−8.4%	−16.8%
Canada	−0.3%	−1.4%	−2.8%	−0.7%	−3.4%	−6.8%	−0.6%	−3.5%	−6.9%	−0.9%	−4.6%	−8.9%
Chile	−0.9%	−4.1%	−8.0%	−2.1%	−9.9%	−19.2%	−2.3%	−10.8%	−21.0%	−3.0%	−14.1%	−27.0%
China	−0.7%	−3.3%	−6.6%	−1.6%	−7.7%	−15.1%	−1.9%	−9.2%	−18.1%	−2.5%	−12.1%	−23.5%
Colombia	−0.6%	−2.5%	−4.8%	−1.7%	−7.4%	−14.2%	−2.1%	−8.8%	−16.7%	−2.7%	−11.4%	−21.7%
Czech Republic	−0.1%	−1.3%	−2.9%	−0.5%	−4.0%	−8.5%	−0.3%	−3.8%	−8.3%	−0.5%	−5.2%	−11.1%
Denmark	0.1%	−0.3%	−0.8%	0.0%	−1.4%	−3.1%	0.3%	−1.1%	−2.8%	0.2%	−1.6%	−3.9%
Egypt	−0.8%	−2.0%	−3.5%	−1.3%	−4.3%	−7.9%	−1.6%	−5.2%	−9.6%	−1.9%	−6.7%	−12.4%
Finland	−0.1%	−0.7%	−1.4%	−0.2%	−2.1%	−4.4%	0.0%	−1.8%	−4.1%	−0.1%	−2.5%	−5.5%
France	−0.3%	−1.7%	−3.5%	−0.9%	−4.9%	−9.9%	−0.9%	−4.9%	−10.0%	−1.2%	−6.5%	−13.1%
Germany	−0.3%	−1.6%	−3.3%	−0.7%	−4.0%	−8.1%	−0.6%	−4.0%	−8.3%	−0.9%	−5.4%	−11.1%
Greece	−0.5%	−1.7%	−3.2%	−1.3%	−4.9%	−9.3%	−1.6%	−5.4%	−10.1%	−1.9%	−6.8%	−13.1%
Hong Kong	−2.6%	−3.0%	−3.8%	−3.9%	−6.4%	−10.1%	−5.9%	−10.3%	−16.3%	−6.3%	−12.0%	−21.2%
Hungary	−0.2%	−1.5%	−3.0%	−0.7%	−4.2%	−8.5%	−0.6%	−4.1%	−8.6%	−0.9%	−5.5%	−11.4%
India	−0.8%	−3.0%	−5.7%	−2.0%	−8.9%	−17.4%	−3.2%	−13.9%	−27.0%	−4.0%	−18.0%	−35.1%
Indonesia	−0.6%	−2.1%	−4.0%	−2.0%	−8.5%	−16.7%	−3.4%	−15.4%	−30.2%	−4.4%	−20.0%	−39.5%
Italy	−0.5%	−2.3%	−4.5%	−1.2%	−5.6%	−11.0%	−1.3%	−5.9%	−11.4%	−1.7%	−7.7%	−14.8%
Japan	−0.3%	−1.6%	−3.2%	−0.8%	−4.2%	−8.4%	−0.8%	−4.5%	−9.1%	−1.1%	−6.0%	−12.0%
Malaysia	−1.2%	−2.8%	−4.8%	−4.0%	−12.3%	−22.3%	−6.8%	−20.1%	−36.3%	−7.8%	−25.2%	−46.2%
Mexico	−0.5%	−1.9%	−3.6%	−1.1%	−4.4%	−8.5%	−1.4%	−5.2%	−9.8%	−1.7%	−6.7%	−12.6%
Netherlands	−0.1%	−0.8%	−1.8%	−0.3%	−2.4%	−5.2%	−0.1%	−2.3%	−5.1%	−0.3%	−3.2%	−7.0%
New Zealand	−0.4%	−1.9%	−3.7%	−1.0%	−4.9%	−9.7%	−1.1%	−5.2%	−10.4%	−1.4%	−6.9%	−13.6%
Norway	0.1%	−0.8%	−1.9%	−0.2%	−2.4%	−5.2%	−0.4%	−2.6%	−5.4%	−0.5%	−3.5%	−7.3%
Peru	−0.5%	−2.5%	−5.1%	−1.0%	−5.1%	−10.0%	−1.1%	−5.7%	−11.3%	−1.4%	−6.9%	−13.7%
Philippines	−1.3%	−3.1%	−5.4%	−3.5%	−11.8%	−21.6%	−5.8%	−19.5%	−35.0%	−6.9%	−24.6%	−43.9%
Poland	−0.2%	−1.4%	−3.0%	−0.6%	−3.8%	−7.9%	−0.5%	−3.8%	−7.9%	−0.8%	−5.1%	−10.6%
Portugal	−0.4%	−1.3%	−2.3%	−0.9%	−3.2%	−6.2%	−1.0%	−3.3%	−6.3%	−1.2%	−4.3%	−8.4%
Romania	−0.5%	−1.8%	−3.3%	−1.1%	−4.5%	−8.7%	−1.3%	−4.7%	−8.9%	−1.6%	−6.0%	−11.5%
Russia	−0.2%	−1.5%	−3.2%	−1.3%	−4.7%	−8.9%	−2.3%	−5.8%	−10.1%	−2.6%	−7.2%	−12.8%
Saudi Arabia	−0.9%	−2.9%	−5.3%	−4.8%	−10.7%	−17.8%	−11.6%	−19.4%	−29.2%	−12.2%	−22.5%	−35.5%
Singapore	−1.0%	−2.7%	−4.9%	−2.9%	−10.6%	−20.2%	−5.0%	−18.6%	−35.6%	−6.1%	−23.9%	−46.4%
South Africa	−0.8%	−3.5%	−6.9%	−1.7%	−7.7%	−14.9%	−2.1%	−9.2%	−17.8%	−2.7%	−12.0%	−23.1%
South Korea	−0.2%	−1.3%	−2.7%	−0.8%	−4.2%	−8.5%	−0.8%	−4.7%	−9.7%	−1.1%	−6.3%	−12.8%
Spain	−0.4%	−1.3%	−2.5%	−0.9%	−3.6%	−7.0%	−1.0%	−3.8%	−7.3%	−1.2%	−4.9%	−9.7%
Sweden	0.0%	−1.1%	−2.5%	−0.3%	−3.1%	−6.6%	0.0%	−2.8%	−6.5%	−0.2%	−4.0%	−8.8%
Switzerland	0.0%	−0.6%	−1.4%	−0.1%	−1.9%	−4.2%	0.1%	−1.8%	−4.4%	0.0%	−2.6%	−6.1%
Taiwan	−0.6%	−2.6%	−5.2%	−1.7%	−7.5%	−14.8%	−2.6%	−11.3%	−22.2%	−3.3%	−14.7%	−29.2%
Thailand	−1.2%	−2.9%	−4.9%	−3.0%	−10.4%	−19.5%	−4.9%	−17.8%	−33.7%	−6.0%	−22.9%	−43.6%
Turkey	−0.2%	−1.2%	−2.5%	−0.6%	−3.3%	−6.7%	−0.6%	−3.8%	−7.8%	−0.9%	−5.0%	−10.3%
UAE	−0.9%	−3.0%	−5.5%	−2.1%	−8.5%	−16.6%	−3.3%	−13.3%	−25.8%	−4.1%	−17.3%	−33.7%
UK	−0.1%	−1.1%	−2.4%	−0.5%	−3.2%	−6.6%	−0.3%	−3.1%	−6.5%	−0.6%	−4.2%	−8.7%
Ukraine	0.2%	0.0%	−0.2%	0.0%	−1.5%	−3.7%	0.3%	−1.3%	−3.6%	0.2%	−1.9%	−5.6%
US	−0.5%	−1.7%	−3.1%	−0.9%	−3.6%	−6.8%	−1.0%	−3.9%	−7.2%	−1.2%	−5.0%	−9.2%
Venezuela	−0.3%	−1.4%	−2.7%	−0.9%	−4.6%	−9.2%	−1.2%	−6.3%	−12.4%	−1.6%	−8.2%	−16.2%

Figure 15: Source: Jessie Guo, Daniel Kubli, & Patrick Saner. (2021). The Economics of Climate Change: No Action not an Option., Swiss Re Institute, institute@swissre.com

Based on the previous Tables, Greece's estimates are shown below. Please keep in mind that all measurements are based on the RCP 8.5 scenario. The chronic physical risk rating is based on the percentage loss of GDP by mid-century under the average 2.6°C warming scenario, but with x10 stress-tested components.

The adaptive capacity ranking is taken from Maplecroft, where it is used as one proxy for transition risk. The table colors represent the various degrees of sensitivity to climate change, with dark green indicating the most resilient and dark red signifying the most seriously damaged countries. (Source: Verisk Maplecroft, Swiss Re Institute). Temperature rises range from pre-industrial to mid-century. The labeling of columns highlights unique variable changes in our scenario analysis: the addition of omitted channels (ie, channels that have not been measured in earlier research) and multiplicative factors (x5 and x10) for potentially enhanced severity of unknown unknowns.

Rank	Country	Physical risk (70%)			Current adaptive capacity (30%)	Climate Economics Index
		Chronic risk (GDP impact) (30%)	Acute risk (extreme weather risk)			
			Dry climate risk score (20%)	Wet climate risk score (20%)		
13	Greece	28	3	25	21	20.3

Temperature path	Well below 2°C increase			2.0°C increase			2.6°C increase			3.2°C increase		
	Paris target			*The likely range of global temperature gains*						*Severe case*		
Omitted channels	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(Un)known unknowns	✗	✓x5	✓x10	✗	✓x5	✓x10	✗	✓x5	✓x10	✗	✓x5	✓x10
Greece	-0.5%	-1.7%	-3.2%	-1.3%	-4.9%	-9.3%	-1.6%	-5.4%	-10.1%	-1.9%	-6.8%	-13.1%

Figure 16: Source: Jessie Guo, Daniel Kubli, & Patrick Saner. (2021). The Economics of Climate Change: No Action not an Option., Swiss Re Institute, institute@swissre.com

2.3 The Impacts of Climate Change on the Energy Sector

The impacts of climate change are in turn expected to have a significant impact on the electricity sector. In terms of production, climate change impacts are expected to result in reduced efficiency and a change in production availability and potential, including thermal and renewable installations.

The effects of climate change on transmission and distribution networks are expected to lead to higher losses, and changes in transmission capacity, while the intensification of extreme weather events will increase the frequency and importance of material damage to energy infrastructure. Also, the effects of climate change are expected to bring changes in energy demand and consumption. In Greece, for example, climate change is expected to bring an increase in energy demand in the summer season, and a decrease in the winter.

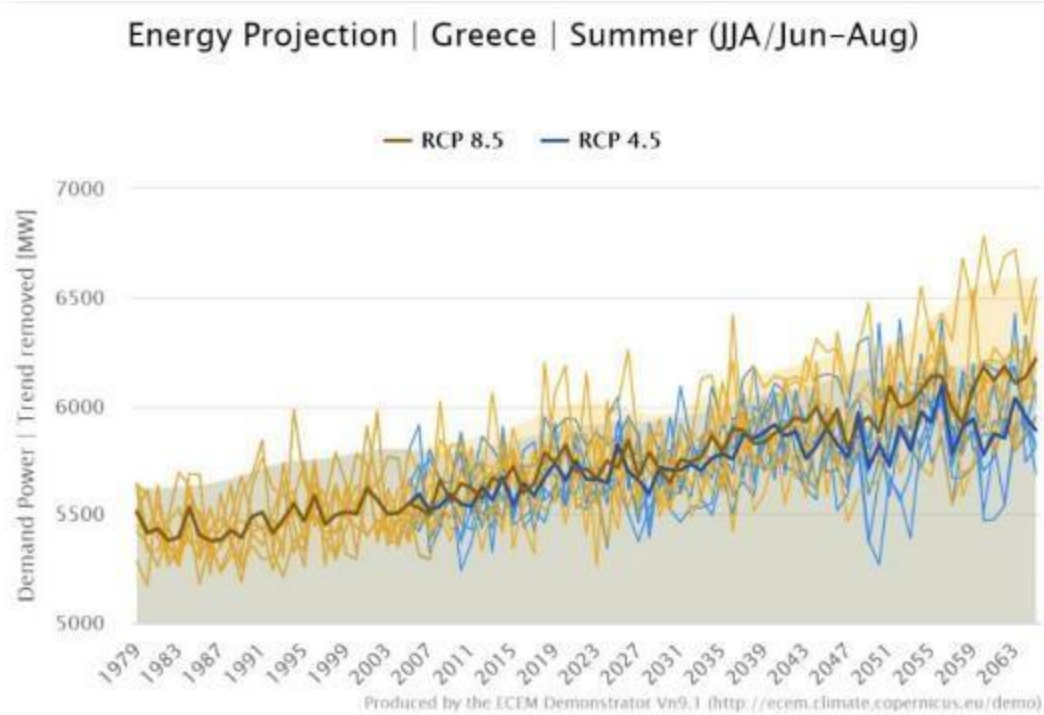


Figure 17: Projected evolution of energy demand during the summer period in Greece in a moderate (RCP 4.5) and high warming (RCP 8.5) scenario.

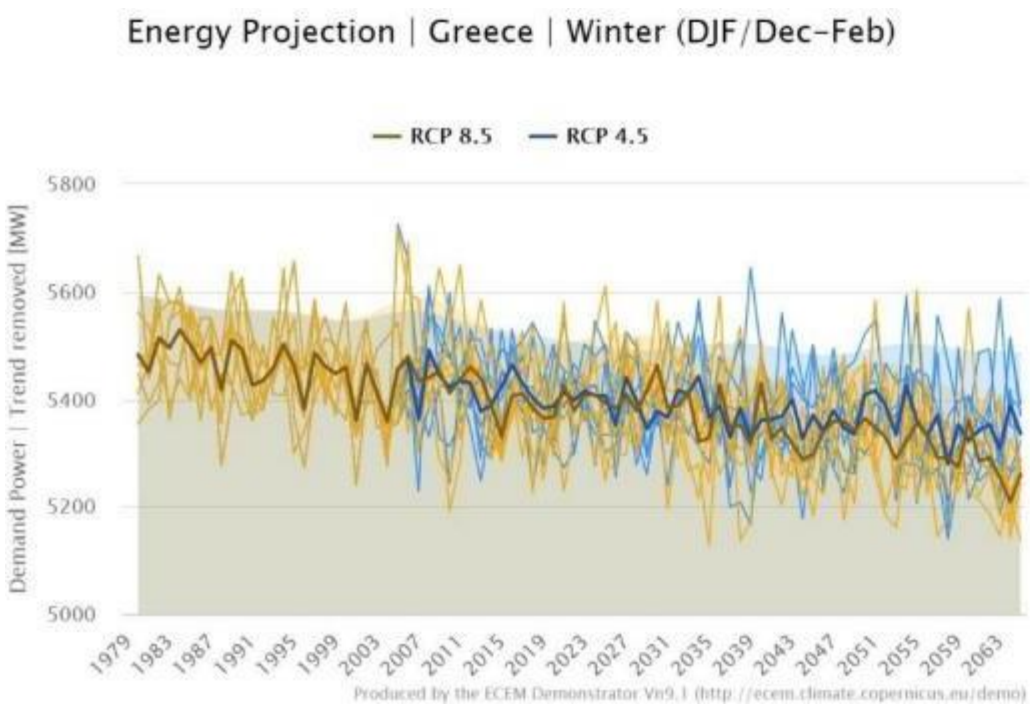


Figure 18: Projected evolution of energy demand during the winter period in Greece in a moderate (RCP 4.5) and high overheating (RCP 8.5) scenario.

The increase in climate anomalies is already a major challenge for electrical systems and increases the likelihood of climate-induced disruptions. In many countries, the increasing frequency or intensity of extreme weather events such as heatwaves, wildfires, cyclones and floods is the leading cause of large-scale power cuts (affecting at least 50,000 customers). The recent shutdowns due to fires and heat waves in California and Australia highlight that electrical systems are already exposed and heavily affected by climate risks. In the United States, 90% of large-scale outages over the past two decades are due to extreme weather events (https://www.iea.org/reports/power-systems-in-transition/climate-resilience). The main impacts on the electricity system due to long-term climate change and extreme weather events are summarised in the following Table.

Table 3: Overview of the impacts of long-term climate change and extreme weather events (source iae.org)

Climate Impact	Electricity Generation	Transmission and Distribution Networks	Demand
Rising temperature	• Efficiency • Cooling efficiency • Production Potential • Power Augmentation	• Efficiency	• Cooling & Heating
Change precipitation patterns	• Production and Potential • Peak Coverage • Renewable energy variability • Technology Application	• Property Damage	• Refrigeration • Water supply
Sea Level Rise	• Production • Property Damage to Affected Facilities	• Property Damage to Affected Facilities	• Water supply
Extreme Weather Events	• Property Damage • Efficiency	• Property Damage • Efficiency	• Refrigeration

It is important to note that electricity plays a critical role in the transition to a low-carbon energy system. Therefore, the lack of resilience in electricity systems can be an obstacle to the clean energy transition, as some renewable energy technologies could be sensitive to a changing climate. This is especially true in countries whose electricity infrastructure is vulnerable to climate change and extreme weather events.

According to a recent study (Energies 2019, 12(24), 4667; https://doi.org/10.3390/en12244667) the main causes of power grid malfunctions can be categorized into three main groups.

Natural causes: natural disasters such as hurricanes, storms, floods, earthquakes, tornadoes, heat waves, lightning, etc.

Errors: causes related to human errors or technical malfunctions of equipment;

Attacks: cyber-attacks such as denial of service or human attacks such as terrorism.

More specifically, as far as natural causes are concerned, the following can be mentioned. Storms can damage power lines and therefore cause power outages through direct or indirect effects (e.g. falling trees). In addition, thunderstorms can increase the rate of lightning, an additional cause of power outages due to damage to power cords. The fall of trees, caused by various factors, including strong winds, accumulation of water on the ground, accumulation of snow or lightning, can also lead to serious material damage. The accumulation of snow on transmission and distribution lines, particularly in conditions of high humidity and temperatures around 0°C (the so-called "wet snow"), can cause power lines and high-voltage power transmission towers to collapse. The following image shows schematically the relationships between the causes of vulnerability and specific vulnerabilities of the power grid.

In the EU, from the monthly statistics of ENTSO-E (2010-2016, 22 Member States), the majority of electricity supply disruption incidents were due to equipment and material failures (40%) as well as extreme weather and natural disasters (33%) – while only 2% of disruptions were due to human error. Also, according to the DSO Observatory Project (DSO-OP) 2018 edition, 80% of these outages are due to failures occurring at the distribution level.

With the increase in the frequency and intensity of extreme natural events due to climate change, it is expected that the proportion of power failure events linked to natural causes will also increase in the coming years. At this point, it is important to note that while the effects of extreme weather events can be estimated to some extent, the effects of longer-term changes are more difficult to predict (due to changes in technical, social, behavioral and economic aspects). But the long-term effects of climate change (such as rising sea levels and higher average temperatures) are expected to have less impact compared to extreme events such as storm surges and heat waves, which can damage power lines, temporarily lose power to users and incur additional restoration costs for electricity providers.

2.3.1 Adaptation and Resilience of the Power Grid

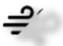
According to the JASPERS guidance on Climate Change adaptation,8 the most significant climatic parameters which are affected by Climate Change, and which can have an impact on network facilities, are the following:

- Temperature - changes in average temperatures, frequency and magnitude of temperature extremes.
- Precipitation (rain, snow, etc.) - changes in average precipitation, frequency and magnitude of extreme precipitation events.

[8] JASPERS Guidance Note, The Basics of Climate Change Adaptation Vulnerability and Risk Assessment, 2017

- Sea level rise - change in relative sea level.
- Wind speed - changes in average wind speeds and maximum wind speeds.
- Solar radiation – changes in the energy from the sun.

Table 4: Impact of the expected climate hazards on the electricity distribution grid in Greece

The following tables summarize the impact of the expected climate hazards on the electricity distribution grid in Greece, classified according to Annex A of regulation (EU) 2020/852 (Taxonomy Regulation), and provides an overview of each hazard's impact on the grid's components. **Climate Variable**		**Climate Hazard**[9]	**Network risk and vulnerability**[10]
	**Temperature** An increase in average and extreme temperatures is expected	Heat wave (prolonged periods with extremely high maximum temperatures)	Extreme temperature events may alter peak electricity demand, while reducing the efficiency and capacity of lines, cables and transformers. This may shorten the lifespan of the network's assets. In addition, exceeding the maximum temperature on the surface of the cables can induce a fire hazard.
		Changing temperature (increase in average temperatures over time)	Increased temperatures may reduce the efficiency and capacity of overhead lines, cables and transformers. Moreover, the sag of overhead lines and cables may also increase.
		Wildfire	Dangerous fire weather could affect components of the network, such as poles, overhead lines and substations.
	**Wind** The geographical distribution of the country's wind potential will remain unchanged	Average wind speed (changes in average wind speed and strength over time)	A small increase in the average wind speed can have a positive effect on overhead lines by cooling them and facilitating heat dissipation.[11] High wind load events can affect the stability of overhead line poles, causing them to topple. In addition, it can cause trees to fall on the lines.
		Storm (including blizzards, dust and sandstorms)[12]	Storms can affect the structure and stability of distribution poles, due to corrosion and stress. Dust storms[13] can affect the operation of overhead transmission lines and substations.

[9] Classification according to Annex A of regulation (EU) 2020/852 (Taxonomy Regulation)
[10] Scientell, Electricity Networks – A guide to climate change and its likely effects, 2022
[11] [Asian Development Bank – Climate Risk and Adaptation in the Electric Power Sector, 2012]
[12] Change in their location, frequency and intensity
[13] Strong wind carrying dust

The following tables summarize the impact of the expected climate hazards on the electricity distribution grid in Greece, classified according to Annex A of regulation (EU) 2020/852 (Taxonomy Regulation), and provides an overview of each hazard's impact on the grid's components. **Climate Variable**		**Climate Hazard**[9]	**Network risk and vulnerability**[10]
	**Water** A decrease in mean annual precipitation and an increase in extreme rainfall events associated with flooding events are expected. In addition, drought-related conditions are expected to intensify.	Heavy precipitation	Extreme rainfall events can cause flooding, which can in turn damage substations and cables (overhead and underground). In addition, they can lead to soil erosion that could affect the stability of overhead poles. Ice and hailstorms can cause damage to exposed network assets. Heavy precipitation can limit access to network assets for repair, causing supply restoration delays.
		Precipitation or hydrological variability	Mean and seasonal rainfall changes can cause maintenance and repair issues to underground cables.
		Drought (prolonged periods of unusually low rainfall, leading to water shortages)	Drought can affect the ground conductivity through underground cables. In addition, ground movement can damage overhead and underground structures.
		Sea-level rise	Sea-level rise can cause an increased rate of inundation and erosion, damaging substations, transformers and poles that are near the coast.

The following tables summarize the impact of the expected climate hazards on the electricity distribution grid in Greece, classified according to Annex A of regulation (EU) 2020/852 (Taxonomy Regulation), and provides an overview of each hazard's impact on the grid's components. **Climate Variable**		**Climate Hazard[9]**	**Network risk and vulnerability[10]**
	Soil mass	Coastal erosion	Strong coastal waves caused by strong winds can result in coastal erosion and potentially serious damage, depending also on the morphology of the coastal areas.
		Subsidence / landslide	Poles and overhead lines can be affected by subsidence / landslides.
	Compound extreme events Potential increase in intensity and frequency	Multiple adverse impacts that occur concurrently or in quick succession	Depending on the events combined, compound extreme events can lead to physical damage of equipment and infrastructure, disruptions to electricity supply, increased customer demand, reduction of the distribution lines' capacity and increased operational costs and network failures.
	Other climate-related hazards	Vegetation Growing degree-days[14]	An increase in growing degree-days can increase the maintenance requirements of overhead lines.
		Lightning strikes	Lightning strikes can disrupt the power supply and accelerate the deterioration of equipment/infrastructure. In addition, they can ignite bushfires.
		Solar radiation	High solar radiation, combined with high temperatures and low winds, creates challenging conditions that can lead to equipment wear.

[14] Period during which the meteorological conditions are particularly favorable for the development of certain species of flora

Asset \ Climate Hazard	ACUTE						CHRONIC			
	Flood	Wildfire	Storm	Heavy precipitation (lightning, heavy rainfall, hail)	Snow and ice load	Heat wave	Drought (incl. Saharan dust)	Humidity	Subsidence/ landslide	Sea level rise
S/S buildings	■	■						■	■	■
Transformers	■	■	■	■	■	■	■	■	■	
Aerial Network (overhead lines and S/S, poles)	■	■	■	■	■	■		■	■	■
Indoor S/S	■	■				■			■	
Switches / Circuit breakers	■	■	■	■	■	■	■	■		
HV/MV Open (outdoor) S/S	■	■	■	■	■			■	■	
Underground network (cables)	■	■	■	■	■	■	■	■	■	■
Electricity Storage Facilities (e.g. batteries or fuel cells)	■	■			■	■			■	■
Protection Equipment (Grounding, Lightning Arrester, etc.)	■	■		■		■				
Protection Automation Control (relays, telemetry, SCADA)	■	■		■	■	■				
Telecommunication network	■	■	■	■					■	

	Climate Risks-ASSETS	MT Overhead Pipeline Network	Underground Cable Network	Substation Buildings	Switches / Disconnectors	Automation Controls	Telecommunication Network
SHOCKS: NATURAL EVENTS	Floods		!	!	!	!	
	Fires	!	!	!	!		!
	Strong winds (storms)	!		!			!
	Thunderstorms (lightning, heavy rain, hail)	!	!	!	!	!	!
	Frost	!			!	!	
	Heat wave / Extreme air temperatures	!				!	
	Earthquakes		!	!		!	!
	Lightning	!					
	Heavy snowfall	!			!		
STRESSES: LONG-TERM BURDEN	Drought	!			!		
	Moisture			!			
	Ground Instability / Landslides / Subsidence			!			!
	Sea Level Rise		!	!			

Finally, in addition to the direct impact of climate risks on energy distribution infrastructure, unexpected changes in energy demand may put pressure on the system. For example, excessive demand for air conditioning on very hot days can affect system efficiency.

We have seen that climate change presents long-term as well as short-term risks. Similarly, addressing these risks requires different approaches, as illustrated in the image below.

	RISK	TREATMENT
RESILIENCE	EXTREME WEATHER EVENTS • Significant Risk to Infrastructure	CRISIS MANAGEMENT PLANNING
LONG-TERM ADAPTATION	LONG-TERM EFFECTS • Impact across the value chain	LONG-TERM PLANNING • Risk and cost assessment for prioritizing actions

Figure 19: Climate Change Risks and Impacts (adapted from WBCSD, "Building a resilient power sector" 2014)

While climate change adaptation aims to maintain the "reliability" of the electricity grid (i.e. security of energy supply) against the most common threats of the future, system resilience is mainly about dealing with extreme weather events.

2.4 Resilience against serious and unforeseen threats regarding the Electricity Sector

The internationally used term "resilience" has been attributed in dictionaries as resilience, endurance, strength, vigor, elasticity, adaptability, and ability to recover, and identifies the ability to recover from difficulties or disorders. Resilience, as the term has prevailed to be rendered in Greek, is a multidimensional concept that covers four dimensions, namely technical, organizational, social, and economic. In engineering and construction, resilience is defined as the ability of structures and infrastructure to absorb shocks without suffering a complete collapse or, more fully, to respond, adapt, and recover from a catastrophic event. In international terminology, the resilience of a system is its ability to resist, absorb, strengthen, and recover from the effects of the risks to which it is exposed in a short period effectively (UNISDR, 2009; UNISDR, 2015).

The resilience of an Electricity Power System (EPS) is defined as its ability to anticipate (through forecasting) and deal with low probability events, which it may not have faced in the past, but with high impact and catastrophic impact on its infrastructure and consequently on its operation (High Impact, Low Probability-HILP events), such as extreme weather events. This term also means the ability of the system to absorb and recover rapidly after the occurrence of such events and to adapt its operation and structure to mitigate their effects. The resilience of a system in simple terms is its ability to cope with the smallest possible losses in very large and unpredictable disasters, such as hurricanes, snowstorms, forest fires, earthquakes, tidal waves. In general, the concept of resilience refers to reducing the impact even in cases where a system breaks down and needs to be restored as soon as possible and with the least possible losses back to normal operation, which the safety and reliability analysis does not include. Strengthening resilience, therefore, aims to "bend" and not "break" in case of extreme events. The essential properties of a durable system are therefore:

1. The ability to predict (anticipation), to avoid downtime.
2. Absorption, i.e. the ability to minimize any damage.
3. The ability to restore its damaged functions and restart its functionality.
4. Adaptability, i.e. the ability of the system to change to cope with a new situation, learning from similar past events.

The properties of a Distribution Network over time can be visualized in stages as an "Attack" on the Network takes place at a time “tE”, and the transition, through degradation and restoration, forms a "resilience triangle".

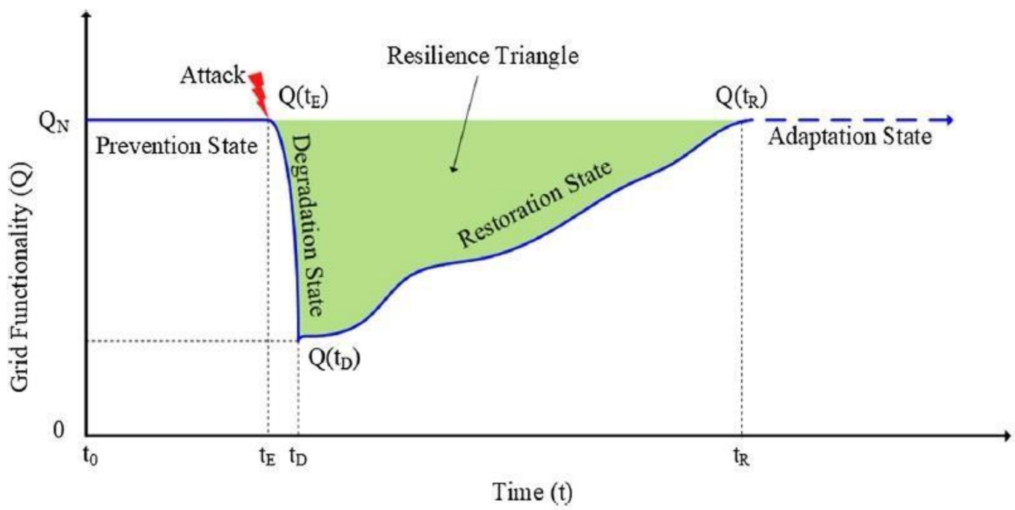


Figure 20: Resilience Triangle (Jufri, 2019)

A conceptual resilience curve plotting the level of resilience as a function of time relative to a disruption event is shown in the next graph.

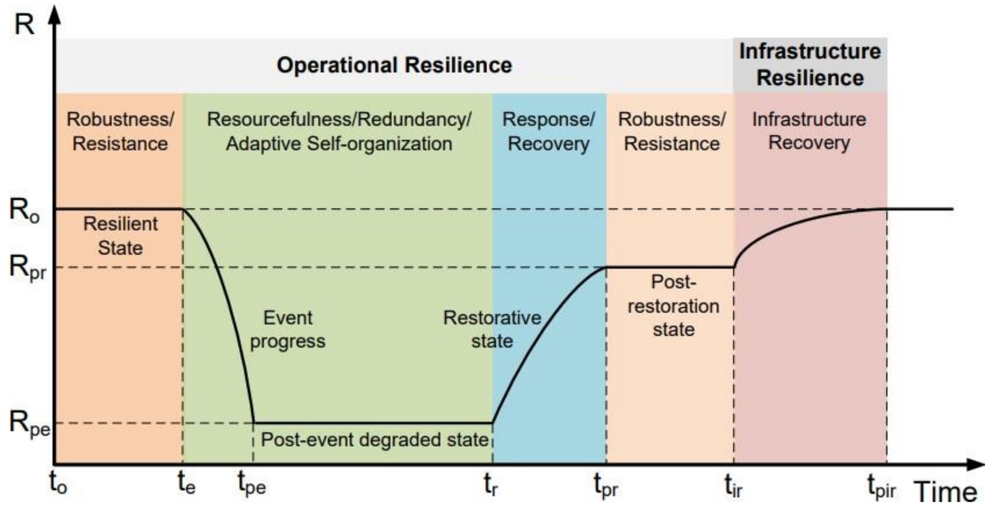


Figure 21: Conceptual resilience curve (Source: Panteli, 2015a)

Based on the above resilience curve, the following results are obtained (Panteli, 2015a):

Before the event occurs at "tE" time, the EES must be robust and durable to withstand the initial shock. A well-designed and functional EPS should demonstrate sufficient resilience (Ro) to deal with any type of incident. After the event, the system enters the post-event degraded state where its resilience is at significant risk (Rpe). Resourcefulness, redundancy, and adaptive self-organization are key traits required at this stage to adapt and cope with evolving conditions (which have probably never been addressed before) to minimize impacts and degradation of resilience (i.e. Ro-Rpe) before the recovery process begins in tr.

The EPC then enters the restorative state, where it must demonstrate the remediation capability necessary to enable quick response and recovery to a resilient state as quickly as possible. Once the post-restoration state is complete, the Rpr resistance level of the EPS may or may not be as high as the pre-event Ro resilience level (i.e. Rpr < Ro). While the EPS may have recovered in terms of a full return to pre-event operational condition (thus demonstrating a certain degree of operational resilience), the infrastructure may take longer to fully resilience. This will depend on the severity of the incident and the resilience characteristics demonstrated by the EPS before, during, and after the external shock.

It is noteworthy that some measures can make the EPS more robust in terms of functionality but less resilient in terms of infrastructure. For example, undergrounding an overhead network section can improve the ability of the power plant to withstand extreme events, but then, if the underground cable is damaged, it can take much longer to repair than an overhead line. This is a critical issue if a new event occurs relatively soon (e.g. wave subsidence after a large earthquake).It should also be stressed that to fully understand and assess the resilience of the EES, both the levels of resilience (Ro, Rpe and Rpr) and the transition times between system states associated with an event (i.e. tpe – te, tpr – tr and tpir – tir, respectively) are required.

One concept related to the resilience of power grids is their reliability: IEEE defines it as the required operational performance for given conditions and time. Historically, the first introduction of probabilistic analysis in EPS was through the concept of reliability. Mathematically, reliability expresses the probability that a system will satisfactorily fulfill its mission. In this context, network reliability is examined by the frequency and duration of service interruptions due to common failures such as short circuits and device malfunctions.

In general, a system is reliable when the probability of failure is very small (e.g. loss of load for less than a day in 10 years). In EPS, reliability is assessed by various indicators relating to production, transmission and distribution. Indicatively, for the production system, the most well-known concept is that of Loss of Load Probability, which is defined as the probability that the production system will not be able to serve the peak load due to the unavailability of some units. Another relevant indicator is the expected Energy Not Served value in MWh.

A summary of the differences between the two concepts (resilience and reliability) for electricity grids is shown in the following Table and the conclusion drawn is that a reliable grid is not necessarily resilient:

Table 5: Summary of the differences between the two concepts (resilience and reliability) for electricity grids

Attribute	Reliability	Resilience
Main feature	• Statics	• Adaptive • Continuous • Short and long term
Probability of an event	• High	• Low
Incident Impact	• Low	• High
System Focus	• Stadium	• Transition time between stages
Landmark	• Customer service downtime	• Downtime of the customer's service and • Infrastructure recovery time
Failures	• Asset failure due to foreseeable causes • Unrelated failures • None/limited differentiation between customers	• Systemic failures in rare and specific events • Multiple associated failures • Critical customers (hospitals, fire brigades, etc.)
Management through:	• Asset failure analysis, replacement policies, and maintenance schedules • Rehabilitation procedures	• Engineered resilience – system strengthening and system flexibility improvements • Disaster response and risk management
Measurement Systems / Indicators	• Well-established - developed over decades • Well-established - developed over decades	• Early stages of development – no single definition • In advance - level of resistance to specific events

The durability of EPS is a term that has been mentioned in Regulation (EC) No. Regulation (EC) No 714/2009 of the European Parliament establishing a European Network of Transmission System Operators for Electricity (ENTSO) which draws up and publishes every two years a Community-wide network development plan. The Community-wide programme should include modelling of the integrated network, scenario development, European generation adequacy forecasting and system resilience assessment.

In addition, Regulation (EU) No. Regulation (EU) No 347/2013 of the European Parliament and of the Council states, inter alia, that the Union's energy infrastructure needs to be upgraded to prevent technical failures and strengthen its resilience to natural or man-made disasters, to prevent the adverse effects of climate change and threats to its security, notably in the case of European critical infrastructure, as defined in Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection.

Common events considered dangerous are those related to extreme weather events, which lead to power cuts and can leave several thousand customers (up to millions) out of power. In the EU, according to the monthly statistics of ENTSO-E (2010-2016, 22 Member States), the majority of electricity supply disruption incidents were due to equipment and material failures (40%) as well as extreme weather conditions and natural disasters (33%).

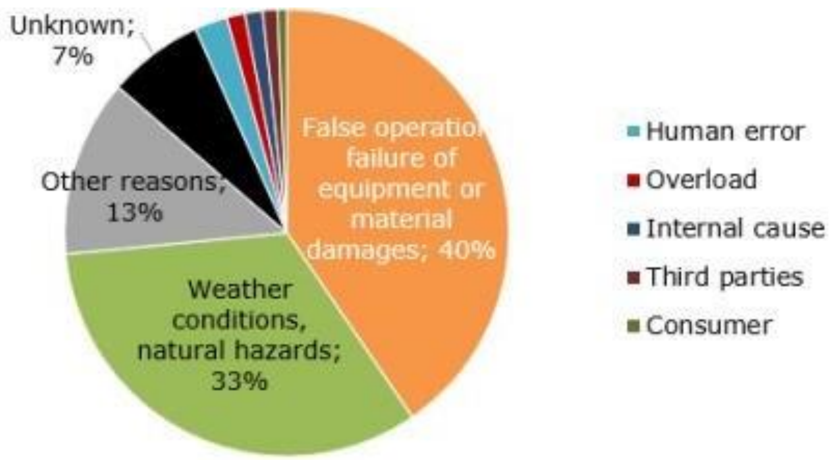


Figure 22: Causes for Disruption Events (Source: EC, 2018)

It should be noted that a major event is a catastrophic event that exceeds the reasonable limits of planning or operation of the EPS. The incident data may reveal clear causality and an obvious solution, such as the need for increased system redundancy, which can improve resilience and contribute to lower SIDI values. However, the issues underlying power outage data can be complex and solutions are often not simple.

Due to the inherent subjectivity in determining significant events, particularly as they relate to weather conditions, the IEEE Working Group on System Design developed a statistically based definition for classifying the days associated with a major event ("MED", known as the 2.5-beta method (IEEE Std. 1366-2012). This method is based on adjusting the daily SAIDI values to a logarithmic normal distribution, then finding the limit in that distribution (TMED) as follows:

TMED = $e^{(\alpha + 2,5\beta)}$

Any days of the following year with a daily SAIDI exceeding TMED are considered MED.

Statistically, days with a daily SAIDI > TMED system are days when the power supply system experiences pressures beyond what is usually expected (such as during extreme weather conditions). This method can be used for the latest 5-year data.

It is worth mentioning that according to[15] the Network Development Plan (CDP) 2021 - 2025 of the Hellenic Electricity Distribution Network Operator (HEDNO) which is under consultation (18/12/2020), HEDNO plans to carry out projects for the five-year period 2021-2025 that will be financed by the Development Fund. The projects are divided into the following actions: HEDNO network upgrades in forest areas: includes projects aimed at improving the reliability of the network and quality indicators, through significant harm reduction and protection of flora and wildlife (e.g. migratory birds). Specifically, this action includes:

- Replacement of bare conductors of overhead MT networks, passing through forest areas, with covered conductors or twisted cables.
- Removal of the overhead network and its replacement with an underground network or alternatively relocation of the overhead network and its routing along a road network where underground is not chosen due to high costs.
- Installation of insulating covers on elements of the network. The purpose of this action is to improve the reliability of the network and quality indicators, through the significant reduction of damage and the protection of flora and wildlife (e.g. migratory birds). Specifically, by limiting the exposure of bare ducts to weather phenomena, temporary or permanent errors due to the contact of foreign bodies or birds on the ducts or the ducts themselves with each other are avoided. Also, through the installation of insulating covers on elements of the Network and the protection of wildlife that this will bring, it is expected that the damage caused by birds to the Network will be reduced.

[15] https://www.deddie.gr/media/7847/%CF%83%CF%87%CE%AD%CE%B4%CE%B9%CE%BF-%CE%B1%CE%BD%CE%AC%CF%80%CF%84%CF%85%CE%BE%CE%B7%CF%82-%CE%B4%CE%B9%CE%BA%CF%84%CF%8D%CE%BF%CF%85-2021_2025-network-development-plan-2021- 2025.pd

- HEDNO network upgrades aimed at enhancing resilience and protecting the environment: this includes projects to upgrade overhead networks, Medium Voltage (MT), by changing the route of the network, by replacing the overhead network with an underground, by changing the construction of overhead networks with more robust ones, by densifying poles, etc. as well as underground networks in settlements of particular cultural or tourist importance and in city centres.

The regulatory framework according to which the investments will be financed is described in RAE's Decision 1431/2020 "Methodology for calculating the required revenue of the Hellenic Electricity Distribution Network Operator" for the revenue of the distribution activity, which will be applied for at least two four-year regulatory periods. According to this, the permitted income of the manager for the periods 2021 -2024 and 2025 - 2028 and therefore its investments will be approved. HEDNO is in the process of preparing its final proposal for the period 2021-2024 in accordance with Decision 1431/2020.

HEDNO's investment program, according to the HRP 2021-2025, which is under consultation, amounts to €2.3 billion and includes a number of strategic projects necessary for the modernization of the Operator, as well as network projects to increase resilience and address climate change. The way these additional investments are financed is crucial and finding any source of financing with low capital costs or subsidy through various funds is a crucial parameter for their implementation.

The Greece 2.0 National Recovery and Resilience Plan, unveiled in 2021, places a significant emphasis on energy investment, particularly under its Green Transition Pillar. With a total allocation of €6.194 billion from the EU’s Recovery and Resilience Facility (RRF), and an estimated mobilized investment of €11.604 billion, a substantial portion is dedicated to the "Power up" initiative. This component, receiving €1.200 billion (8% of all RRF grants), focuses on critical energy-related projects. Power up aims at strengthening electricity interconnections, promoting Renewable Energy Sources (RES), enhancing energy supply security, and addressing climate change challenges, with an anticipated total investment of €2.348 billion.

Aligned with the EU Green Deal strategy, Power up pursues key goals such as the green transition, greenhouse gas reduction, increased RES utilization, energy security, and the resilience of interconnection infrastructures. To achieve these goals, proposed reforms include restructuring the RES Combined Heat and Power Account (ELAPE) and streamlining the new electricity market model, accelerating licensing procedures for new RES plants (€200 million). The six investments linked to Power up objectives encompass electric energy storage systems, restoration of old lignite mine territories, initiatives for enhanced island interconnection, modernization of urban electricity distribution networks, forest area network upgrades, and increased power capacity in substations to facilitate new RES integration.

2.4.1 The Greek Energy Landscape

As fuel combustion remains the primary source of carbon dioxide emissions, transforming the energy and electricity landscape becomes crucial in mitigating climate change. Greece has committed to complying with this cause by aligning its national climate plans with European objectives, establishing its targets for renewable energy integration, carbon dioxide reduction, and the gradual phase-out of lignite in electricity generation. Energy transition for Greece, as evidently for many other countries, is a critical prerequisite to attaining climate targets while simultaneously improving energy security and reducing dependence on fossil fuels and energy imports. However, the clean energy transition necessitates significant investments over the coming decades, not only in infrastructure but also in research and innovation, which can be supported by both the private and the public sectors.

- PPC remains the largest electricity producer and supplier in Greece, boasting the highest installed capacity. While PPC maintains a strong presence in the Greek electricity market, reduced shares signal increased competition and decreased market concentration.
- The generation of electricity involves the conversion of various energy sources into electrical energy. In 2021, Greece's total electricity production amounted to 54.7 thousand GWh, marking an 8% cumulative reduction over the decade from 2011 to 2021.
- During 2021, the balance between electricity generated from renewable energy sources and biofuels versus fossil fuels in Greece was approximately 40%-60%.
- The Greek energy market is compliant with the EU’s Target Model and operates via the HEnEx, which oversees four wholesale electricity markets within the Interconnected electricity system: a) the Forward Market, b) the Day-Ahead Market, c) the Intra-Day Market and d) the Balancing market.
- CO2 emissions primarily stem from the burning of fossil fuels in the energy sector. Concurrently, the most significant source of emissions within the energy sector is the combustion of fuels for electricity and heat generation.
- The recent energy crisis has significantly contributed to expediting the global shift from fossil fuels to renewables, rendering the latter more competitive and gaining

reinforcement through national initiatives like the REPower EU Plan, aimed at enhancing energy security.

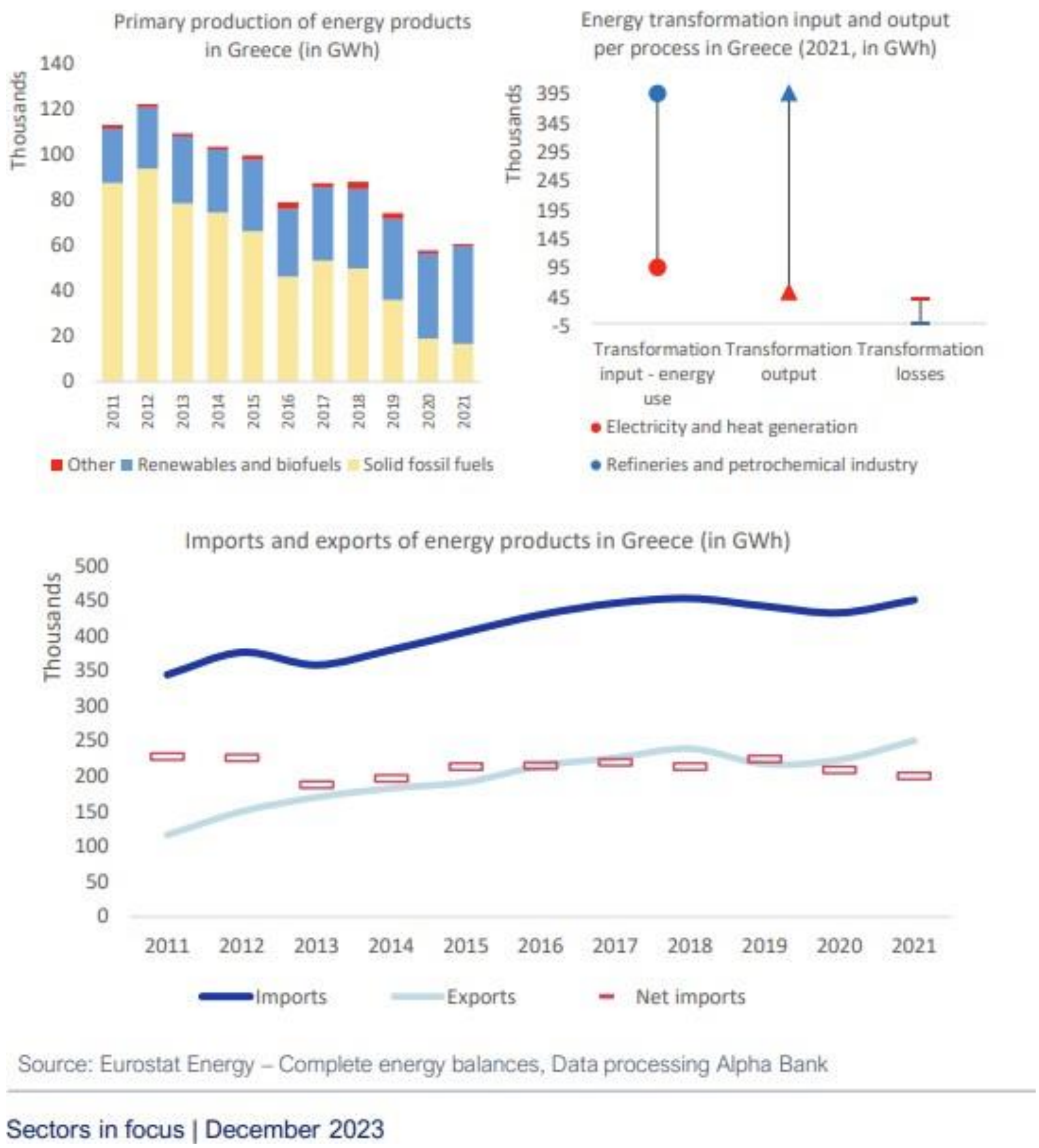


Figure 23: Dr. Kapopoulos E., Dr. Thomaidou F., & Kati S. (2023). Electricity: Renewable Energy Sources and the power landscape in Greece, Alpha Bank - Economic Research Division, alphabankeconomicresearch@alpha.gr

Greece has undergone a notable energy transformation in the last decade, moving from solid fossil fuels, primarily lignite, to a greater reliance on renewable sources. In 2011, lignite made up 78% of primary energy production, but by 2021, it dropped to 28%, while renewables and biofuels increased to 71%. This shift is attributed to the government's commitment to reducing emissions and the growing competitiveness of renewable technologies.

Energy is used for both final consumption (15%) and transformation processes (85%), producing electricity for domestic use and oil refinery products for export. Energy imports, mainly oil and natural gas, rose from 344.2 th. GWh in 2011 to 450.8 th. GWh in 2021. Oil and petroleum products constituted 83% of imports, growing 31%, while natural gas imports increased by 37%. Energy exports include refined oil products (98%) and a small portion of electricity (2%), totaling 250 th. GWh in 2021.

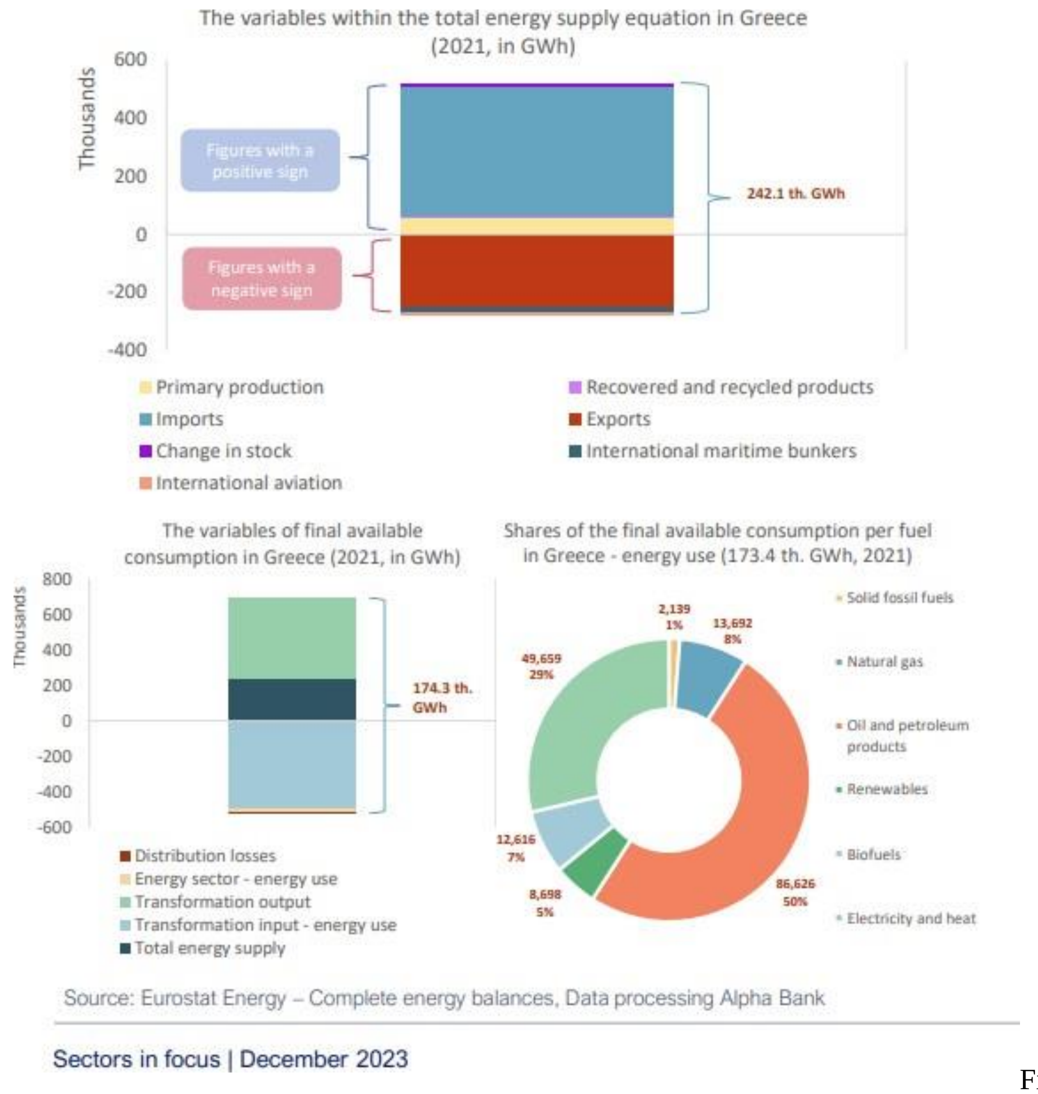


Figure 24: Dr. Kapopoulos E., Dr. Thomaidou F., & Kati S. (2023). Electricity: Renewable Energy Sources and the power landscape in Greece, Alpha Bank - Economic Research Division, alphabankeconomicresearch@alpha.gr

The energy system can be divided into two main components: the total energy supply and the total available energy for final consumption. The available energy for final consumption can be also expressed as the sum of consumption for energy use purposes and for non-energy purposes (while excluding any statistical differences).

2.4.2 Structure of the Electricity Sector

The electricity sector involves distinct processes: production, transmission, distribution, and trade. Production encompasses various methods such as thermal, nuclear, hydroelectric, gas turbine, diesel, and renewable energy sources. Producers include those generating electricity for sale (main activity producers) and those generating it for their own needs (auto producers). Transmission involves conveying electricity from generation facilities to the distribution system, minimizing losses over long distances. It transfers high and very high voltage electricity to suppliers and large consumers through the interconnected transmission system. Distribution operates systems delivering power from generation or transmission to the final consumer via medium and low-voltage networks. Electricity trade involves buying and selling, including selling to end-users, acting as intermediaries, and operating exchanges for power trading. This comprehensive framework outlines the key facets of electricity production, transmission, distribution, and trade within the industry.

2.4.3 Main Metrics of the Greek Electricity Sector:

In 2020, the Greek electricity industry, with over 29,000 employees and nearly 9,000 enterprises, showed resilience during the COVID-19 crisis. It contributed over €3 billion in value-added, experiencing a 6% increase in turnover to €14.5 billion. Greece actively participates in the EU's Electricity Market, engaging in trade, with net imports totaling 3.7 th. GWh in 2021. Key trading partners include Turkey, Bulgaria, Italy, Albania, and North Macedonia.

In the electricity subsectors, production dominates employment (67% of the workforce and 96% of enterprises), while distribution employs 22% of workers. Despite negative value added, electricity trade contributes significantly to turnover (21% of the total) and enterprises (3%). Electricity transmission, crucial for the sector, represents 9% of Gross Value Added, 5% of employment, and 3% of turnover as of 2020. The industry's performance reflects its robustness amid external challenges.

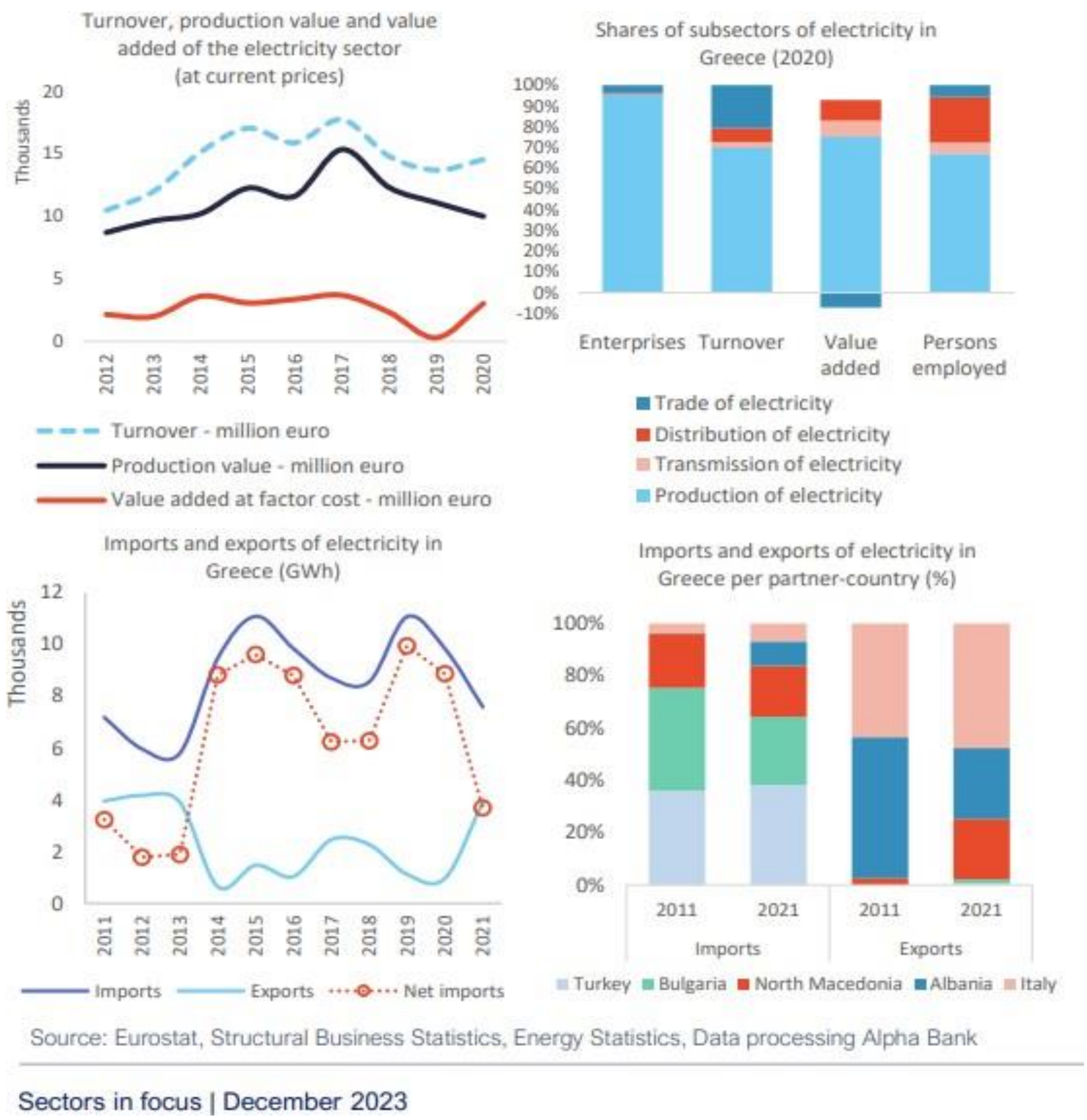


Figure 25: Dr. Kapopoulos E., Dr. Thomaidou F., & Kati S. (2023). Electricity: Renewable Energy Sources and the power landscape in Greece, Alpha Bank - Economic Research Division, alphabankeconomicresearch@alpha.gr

A decade ago, Greece heavily relied on fossil fuels for electricity generation. While there has been a notable increase in the incorporation of Renewable Energy Sources (RES), transforming the energy mix, fossil fuels still constitute a significant 59% of gross electricity production in 2021. Fossil energy, characterized by non-renewable hydrocarbon-based fuels like coal, oil, and natural gas, contributes to CO_2 emissions when combusted.

Greece's current electricity production prominently features renewable sources such as solar, hydropower, and wind energy. The process of electricity generation involves converting diverse energy sources into electrical energy. Within this domain, gross production encompasses the total output, including energy for plant operations. In contrast, net production represents the electricity available to consumers after deducting the plant's internal energy consumption, referred to as auxiliary consumption. An increase in net production compared to gross production indicates enhanced resource efficiency in the power sector, showcasing a positive trend.

2.4.4 The Electrical Power Market

In the electricity sector, companies engage in various activities spanning generation, transmission, distribution, and trade. A notable example is the Public Power Corporation (PPC), Greece's largest electricity producer and supplier, boasting an installed capacity of 11.1 GW from power stations like lignite-fired plants, hydroelectric facilities, and other Renewable Energy Sources (RES). Despite PPC's dominance, market shares have decreased, indicating heightened competition and reduced market concentration. In 2021, PPC's share of installed capacity dropped from 60% in 2016 to 43%, with other companies holding at least 5% accounting for 18%.

Regarding electricity generation delivered to the grid, PPC represented 45% in 2021, while other companies with at least 5% collectively accounted for 18%. In net production from fossil fuels and large-scale hydro units, PPC's share reached 62%. Besides PPC, significant conventional and RES generators include ELPEDISON, MYTILINEOS Group subsidiaries like Korinthos Power, and HERON, a TERNA Group subsidiary. Despite a reduced consumption share, PPC manages 73% of medium and low voltage electricity meters.

Electricity retailers in Greece include various companies such as ELPEDISON, Protergia, HERON, Zenith, NRG, Watt & Volt, Fysiko Aerio, Volton, KEN, Volterra, ELINOIL, OTE Estate, and ELTA. In electricity transmission and distribution, IPTO and HEDNO operate as natural monopolies. The landscape reflects a diversified industry with competition, and PPC, despite a decreased market share, remains a significant player in various aspects of the electricity sector.

Figure 26: Dr. Kapopoulos E., Dr. Thomaidou F., & Kati S. (2023). Electricity: Renewable Energy Sources and the power landscape in Greece, Alpha Bank - Economic Research Division, alphabankeconomicresearch@alpha.gr

2.5 Financial Performance of the Electricity Market

ICAP's financial database, Dataprisma, reveals a substantial 70% increase in electricity industry subsector revenues in 2022 compared to 2021, based on data from large, medium, and small companies. However, mixed profits saw only a modest 2% uptick. The electricity sector's total assets remained constant at €37 billion. In electricity generation, a significant revenue boost of 86% in 2022, following a 43% increase in 2021, is attributed to the Ukraine-Russia war's energy crisis, resulting in higher input costs. Electricity producers contribute over 80% to total revenues, nearly 78% to mixed profits, and 73% to total assets in 2022. The EBITDA margin dropped from 18.4% in 2021 to 7.7% in 2022.

In the electricity trade subsector, companies represent 9% of total sales, contributing 6% to mixed profits and accounting for 2% of total assets, with an EBITDA margin of 5.6% in 2022. ADMIE and DEDDIE, operating as natural monopolies in electricity transmission and distribution, constitute 1% and 4%, respectively, of total turnover in 2022, contributing 13% and 3% to mixed profits. In 2022, IPTO and HEDNO's EBITDA margins stood at 66.9% and 44.9%, reflecting their monopolistic advantage.

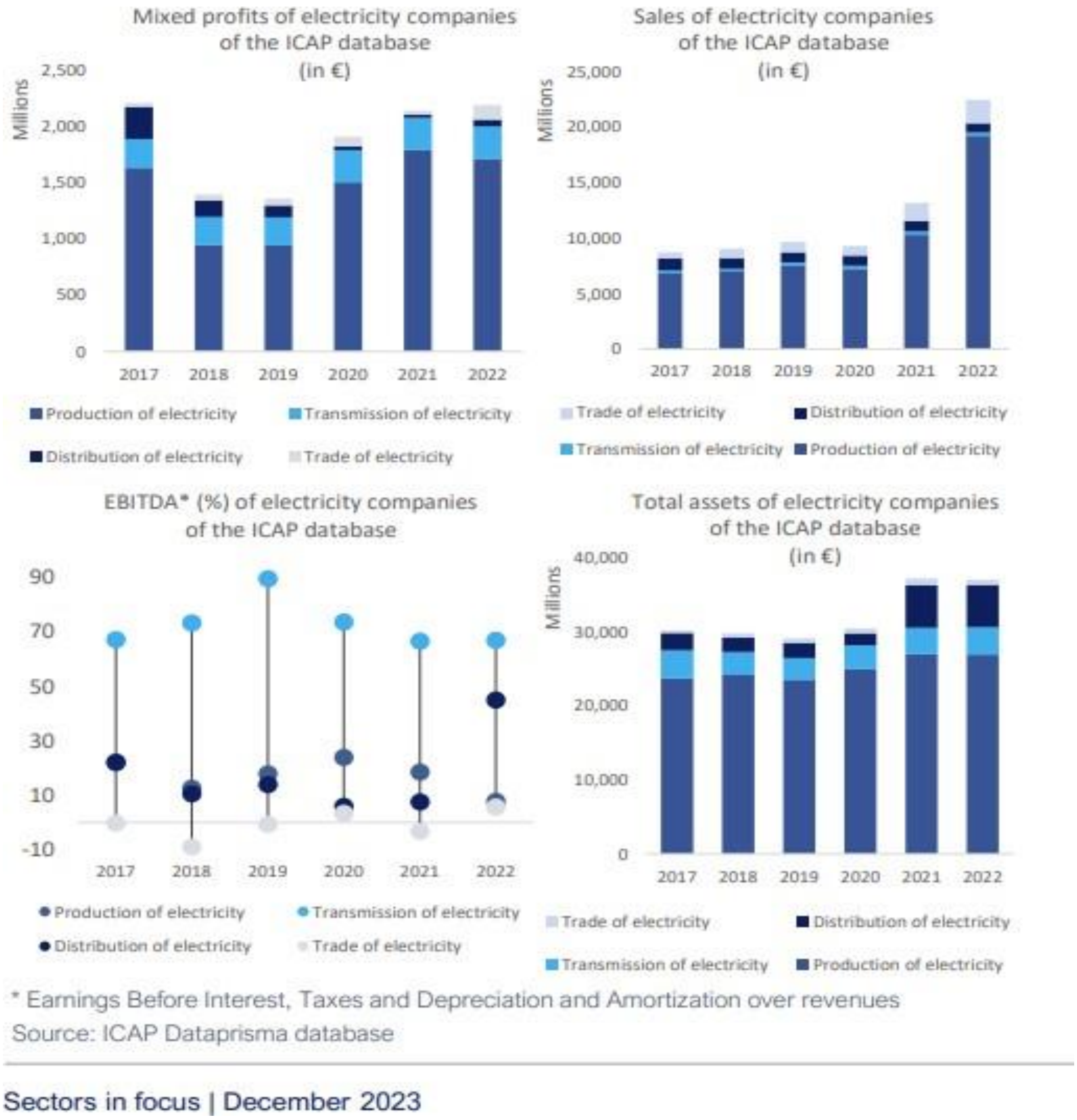


Figure 27: Dr. Kapopoulos E., Dr. Thomaidou F., & Kati S. (2023). Electricity: Renewable Energy Sources and the power landscape in Greece, Alpha Bank - Economic Research Division, alphabankeconomicresearch@alpha.gr

2.5.1 The Greek Interconnected system of electricity

The interconnected electricity system, commonly referred to as the power grid, facilitates the connection between electricity production units, conventional and renewable, and residential and non-residential electricity consumers. Electricity is distributed to consumers through the Hellenic Electricity Distribution Network, which links to the power grid at substations, at which electricity is transformed from very high and high voltage -ideal for efficient long-distance transmission- to medium and low voltage, ensuring safer usage for consumers. The Greek power grid, operated by ADMIE/IPTO, the Public Power Corporation's Transmission System Operator, consists of over 13,000 km of transmission lines, enabling the transfer of electricity throughout mainland Greece, and connecting various islands such as those in Western Greece (Crete, Skiathos, and the Cyclades islands of Naxos, Andros, Syros, Tinos, Paros, and Mykonos). The grid comprises a combination of overhead lines, underground lines, and subsea cables, all operating at very high and high voltage levels (66kV, 150 kV, 400kV) and substations. The core of the system involves three 400kV lines, responsible for the transmission of electricity, primarily from the major production center located in Western Macedonia to the central and southern regions of Greece.

The interconnected electricity grid is an important part of Greece's energy infrastructure, playing a key role in the country's clean energy transition: Recent expansion with Bulgaria is complete, and a 2GW interconnector is expected to be operational by 2028. Plans and proposals also include a) a 3GW interconnection between Egypt and Europe via Greece (EuroAfrica project), b) linking Cyprus and Israel's grids to Europe through Greece, c) smaller interconnections with Balkan neighbors like Albania and Romania, and d) a Greece-Austria-Germany (GAG) interconnector of up to 9 GW of electricity from Greek renewable power capacity, set to be operational by 2030 (ADMIE 2023, RAE 2021, IEA 2023, renewablesnow.com).

2.6 Main institutional entities and operators of the Greek Power System

The Regulatory Authority for Energy, now known as RAAEY, serves as an independent regulatory body overseeing energy and electricity markets. Responsible for monitoring both wholesale and retail energy markets, RAAEY ensures fair competition and stable prices, aligning its objectives with energy policy targets such as market liberalization and environmental protection. The Hellenic Energy Exchange Market (HEnEx-EXE), designated as the Nominated Electricity Market Operator by RAAEY, began operations in November 2020. Operating various markets within the wholesale electricity market, including the Forward, Day-ahead, and Intra-day markets, HEnEx-EXE plays a crucial role in Greece's energy landscape (www.rae.gr, www.henex.gr).

The Independent Power Transmission Operator (IPTO-ADMIE) oversees the Hellenic Electricity Transmission System (HETS-ESMIE), facilitating cross-border electricity trade and managing the Balancing Market within the wholesale electricity sector. Established in 1995 and privatized in 2017, IPTO operates under ADMIE, mainly owned by the Greek government, ensuring reliable and efficient electricity transmission (www.admie.gr).

The Operator of RES and Guarantees of Origin (DAPEEP), founded in 2009, succeeded the Hellenic Electricity Market Operator. As a non-profit organization, DAPEEP is pivotal in Greece's renewable energy sector, managing the Guarantees of Origin system, auctioning emission rights, and administering the Special Account for RES and CHP, supporting the development of renewable energy projects (www.dapeep.gr).

Hellenic Electricity Distribution Network Operator (HEDNO), a subsidiary of PPC, operates and maintains the Hellenic Electricity Distribution Network (HEDN-EDDIE) development of the HEDN, which includes medium and low voltage systems. DEDDIE also manages the markets of the nonconnected islands. HEDNO’s primary focus is to ensure equal access to the HEDN for consumers, providers, and suppliers, promoting fairness and efficiency in electricity distribution (www.deddie.gr).

The Hellenic Electrical Power Station is an interconnected network for the transmission and distribution of electricity from producers to consumers.

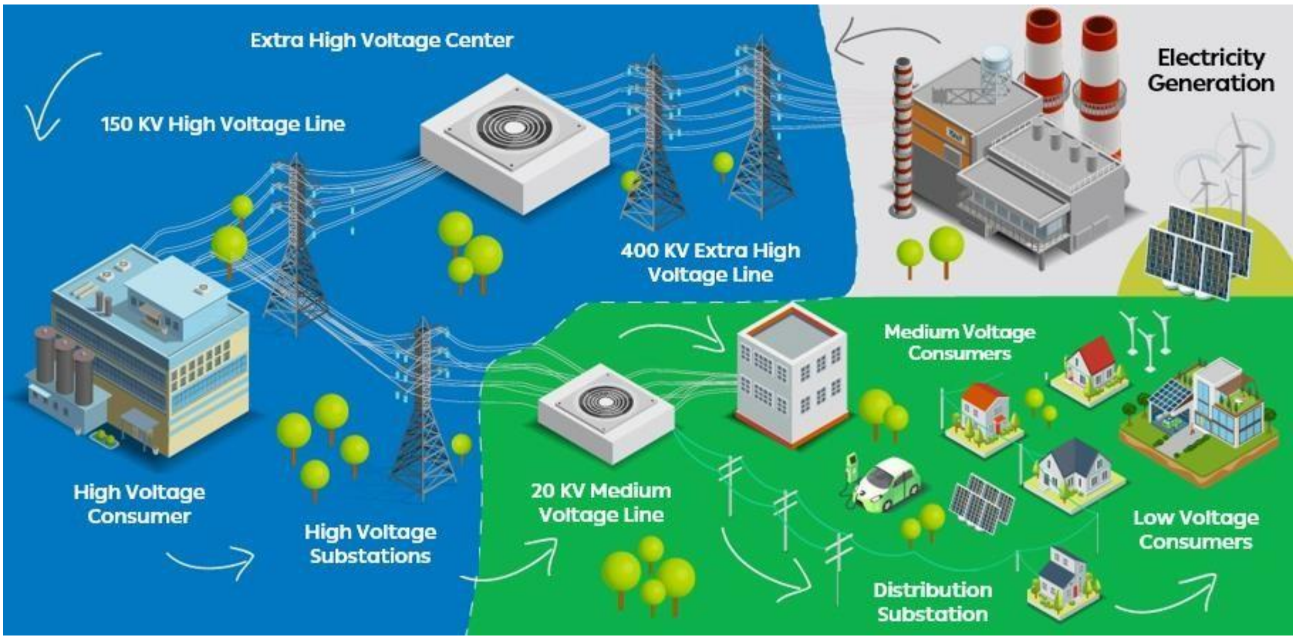


Figure 28: Source: Structure of the Greek Electricity System – HEDNO

It consists of three (3) parts:

Power Plants: Power plants generate electricity using fossil fuels (coal, natural gas, biomass) or air, water, nuclear fuel and sun.

Transmission of Electricity: The purpose of the Transmission System is the connection of power stations (conventional or RES) and the transmission of electricity from production points to consumption points (urban centers, industries). In order to achieve this in the best and most efficient way, the voltage is raised in the connection submarines of the power stations to the levels of 400kV and 150kV and downgraded in the connection submarines to the Distribution Network.

The basic elements of the Transmission System are:

- Overhead transmission lines 400kV, 150kV and 66kV
- Underground and submarine cable lines 150kV and 400kV
- H/S HV/MT, either open, semi-closed or closed type (Distribution Centers, M/R)
- Extra High Voltage Centers (RIC) 400/150kV
- Electricity Distribution: The energy reaches the submarines, voltage is degraded with the help of M/S and is transferred through distribution lines, with further voltage degradation, so it is used by domestic networks.

Key elements of the Distribution Network are:

- HV cable lines in Attica
- HV lines in NII (150 kV and 66 kV)
- MT lines (overhead, underground, underwater)
- H/S MT/LV serving distribution loads and may be air or ground (compressed type or indoor)
- XT Lines

2.6.1 Regulatory Framework of Hellenic Distribution Network Operator

The Electricity Distribution Network in Greece is undoubtedly a vital "nervous system" that distributes electricity throughout the country, from HV consumers to MT and LV consumers, many which concern households.

The Hellenic Electricity Distribution Network Operator (HEDNO) was established by Law 4001/2011 (Government Gazette A' 179/22.08.2011), which incorporated into Greek legislation the provisions of Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 (Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing

Directive 2003/54/EC). Directive 2009/72/EC, which determined the functioning of the electricity market, obliged electricity companies to separate the activities of generation legally and functionally, transmission (HV networks), distribution (MT and LV networks) and electricity trading. Production and marketing were defined as liberalized activities exposed to competition, while transmission and distribution were defined as monopoly activities under regulatory control.

As stated in the relevant directive, the rationale for these changes was that without efficient unbundling of networks from production and marketing, there was a significant risk of "discriminatory behavior in the operation of networks in favor of commercialization, but also a risk of incentives for vertically integrated companies to invest adequately in the networks they own".

The above Law gives HEDNO two (2) distinct responsibilities: those concerning the Management of the Greek Electricity Distribution Network (EDNO) and those concerning the Management of the Electrical Systems (IS) of the Non-Interconnected Islands (NII). HEDNO is designated as responsible for:

- The development, operation and maintenance, under economic conditions, of HEDNO to ensure its reliable, efficient and safe operation, as well as its long-term ability to meet reasonable electricity needs, with due regard for the environment and energy efficiency, as well as to ensure, in the most economical, transparent, direct and non-discriminatory manner; users' access to EDNO, to carry out their activities, under the EDNO Management License granted to it following the provisions of Law 4001/2011 and by the EDNO Management Code. EDNO consists of MT and LV lines, electricity distribution facilities, as well as HV lines and installations that have been integrated into this network. The HV lines belonging to the Network are the 150 kV underground cable lines of Attica, as well as the transmission lines (GM) and underground cables in the NII regardless of voltage level. The network, apart from the NII network, is connected to the Hellenic Electricity Transmission System (HETS) via the HV/MT submarines.
- The management of the Electrical Systems of the NII which includes the management of production, the operation of the market and the systems of these islands.

Apart from Law 4001/2011, the main regulatory text that defines the responsibilities of HEDNO is the Code for the Management of the Greek Electricity Distribution Network (KDD), which was approved by Decision 395/2016 of the Regulatory Authority for Energy (RAE) – specifically

Government Gazette B΄78 / 20.01.2017 - RAE 395 / 18.10.2016. The content of the Code regulates the rights and obligations of HEDNO, Network users and suppliers as well as issues relating to the development, operation, access to the Network, the services provided by the Network Operator and its financial consideration.

The NII Electrical Systems Management Code (NII) defines how NIIs' NIIs are managed. In particular, it defines the framework for the operation and management of the autonomous NII NIIs and the electricity market in the NIIs.

Today, the Company's share capital is 51% owned by PPC S.A. and 49% by Macquarie Asset Management. The activity of managing Distribution Networks is a natural monopoly in the area in which it is carried out as there is no competition. For this reason, these activities are supervised and regulated by the independent Regulatory Authority for Energy and Water Waste (RAAEY - former RAE). In summary, the works carried out by HEDNO concern the following:

Satisfaction of Network users' requests

- New connections between consumers and producers
- Modification of old supplies (increase of power of existing connections)
- Network Shifts

Development of the Network

- Reinforcement, improvements and modernisation of the Network
- Construction of Distribution Centres and 150 kV lines

Operation of the Network

- Operation of the Distribution Network
- Inspection and maintenance of the Network
- Fault repair
- Service of Network users at the offices
- Enumeration of consumption

1. **Smooth and efficient operation of the electricity market at grid level**
2. **Reliable and economical operation of autonomous island electrical systems**

Of course, one of the major challenges that HEDNO is called upon to face is to ensure the uninterrupted distribution of electricity to isolated island systems, which concern islands with different sizes, populations and needs, variables that are reflected in the sharp fluctuations in electricity demand. Indicatively, about 15% of the country's population lives in the NII, where 14% of national annual consumption is consumed, with demand showing an upward trend given the tourist increase.

2.6.2 Characteristics of the Greek Distribution Network

The Hellenic Distribution Network operates at (3) three voltage levels: high (150/66 kV), medium (22/20/15/6.6 kV) and low (0.4 kV). All MT networks on the mainland operate at 20 kV, with the exception of the part of the Attica network, which operates at 22 kV. It is noted that the distribution subsystem 22/6,6kV, which exists only in the Region of Attica, It is planned to be partially abolished within five (5) years. The phase-out will simplify logistics and maintenance and help reduce energy losses through fewer M/S and further voltage increase downstream of the system.

The main quantitative figures of the Distribution Network based on HEDNO data for the year 2021 are presented below:

- 243,150 km MT and LV Network (114,280 km MT Network and 128,870 km LV Network).
- 7,648,284 active customers (14,018 MT customers and 7,634,266 LV customers).
- 6,283,186 MWh production from RES.

HEDNO belongs to the 10 largest Electricity Distribution Operators in the EU, having as its primary objective the uninterrupted distribution of electricity to the entire range of consumers in the Greek territory, with all the difficulties and peculiarities that exist due to the mountainous terrain and the plethora of inhabited islands.

2.6.3 Geographical Organization

HEDNO serves five (5) Regions: Attica, Macedonia – Thrace, Central Greece, Peloponnese – Epirus and Islands. Attica has the largest number of connection points (over 2.5 million) and at the same time is the smallest geographical service area of HEDNO (approximately 4,000 km2). The largest service area is the Region of Macedonia – Thrace which is the region with the largest volume of assets, followed by the Region of Peloponnese – Epirus. According to the Distribution Statistics for the year 2021, the Region of Attica consumes the largest amount of electricity, representing 34% of total consumption, followed by the Region of Macedonia – Thrace which consumes about 24%. The Regions of Peloponnese-Epirus, Central Greece and Islands consume 17%, 13% and 12% respectively.

2.6.4 Number of Users

Below are summary results of the number of users and energy consumption per use. Active users are those who have a valid electricity supply contract, while inactive users are those who do not have a supply contract in force in the period in question, but had within the previous three years.

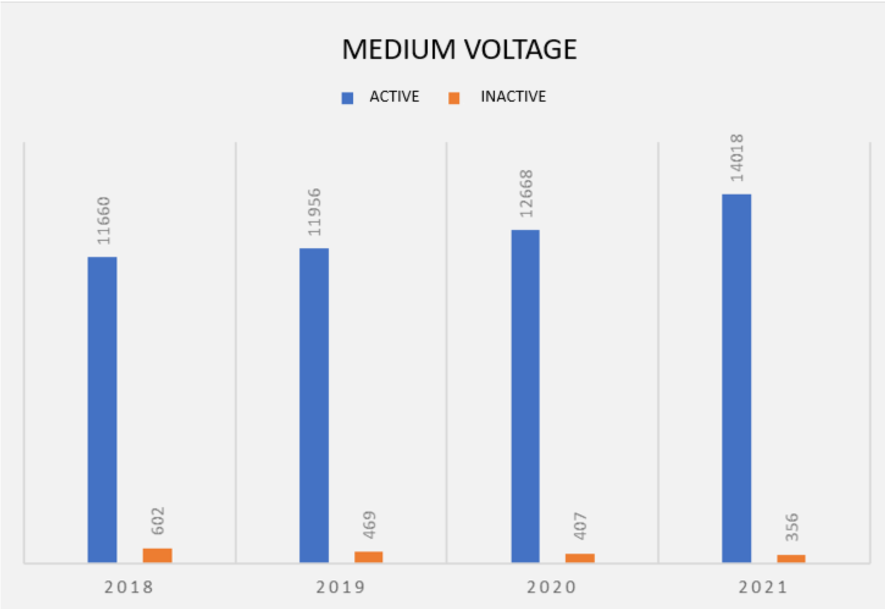


Figure 29: Evolution of HEDNO Users for the years 2018-2021 in MT (Source: HEDNO, HRD 2022-2026)

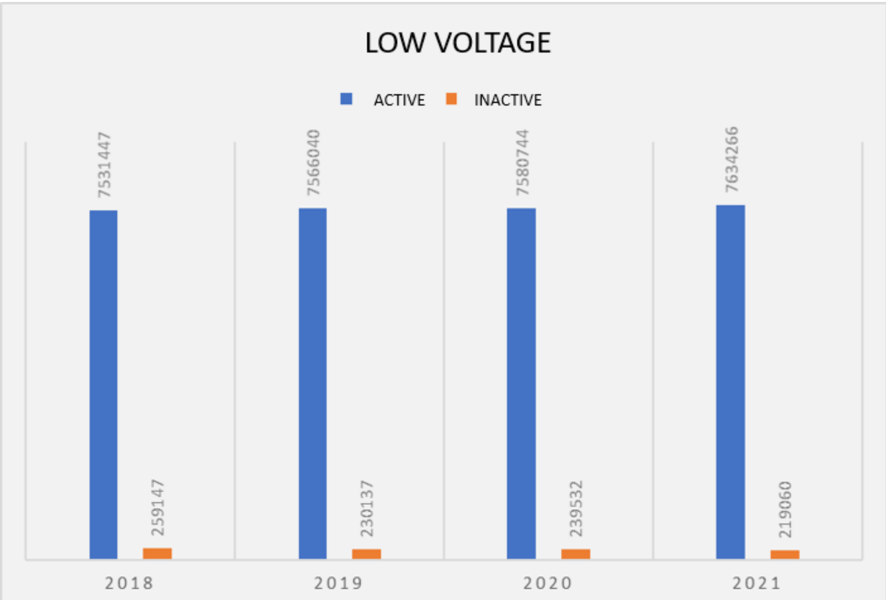


Figure 30: Evolution of HEDNO Users for the years 2018-2021 in LV (Source: HEDNO, HRD 2022-2026)

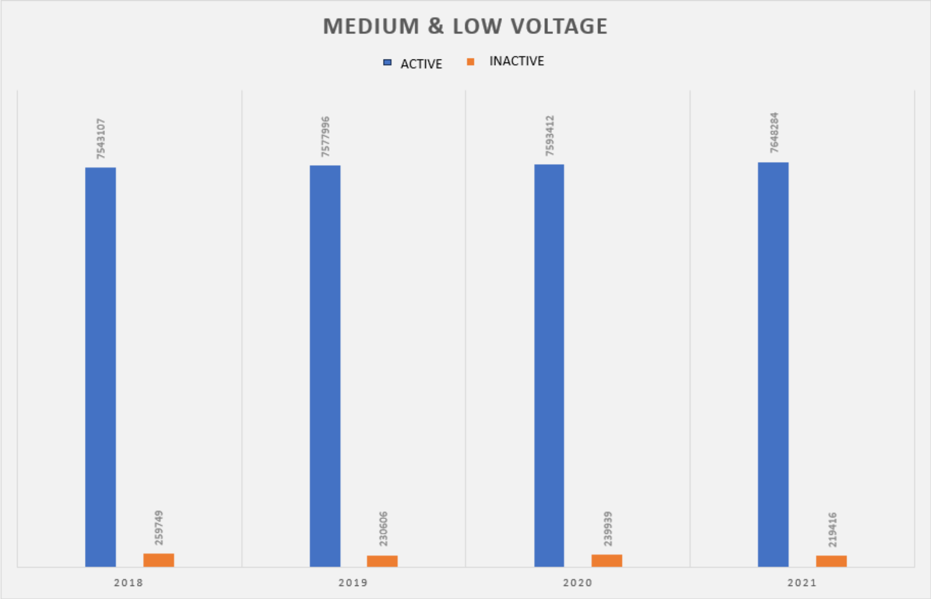


Figure 31: Evolution of HEDNO Users for the years 2018 to 2021 for the total MT and CFT (Source: HEDNO, PPS 2022-2026)

Table 6: Number of Users in the Interconnected System and Non Interconnected Islands per voltage (31.12.2021) (Source: HEDNO, Distribution Statistics for the Year 2021)

Consumers	IS	NIIs	Total
Low Voltage			
Active	6,830,468	803,798	7,634,266
Inactive	196,330	22,730	219,060
Total LV	7,026,798	826,528	7,853,326
Medium Voltage			
Active	12,799	1,219	14,018
Inactive	326	30	356
Total MT	13,125	1,249	14,374

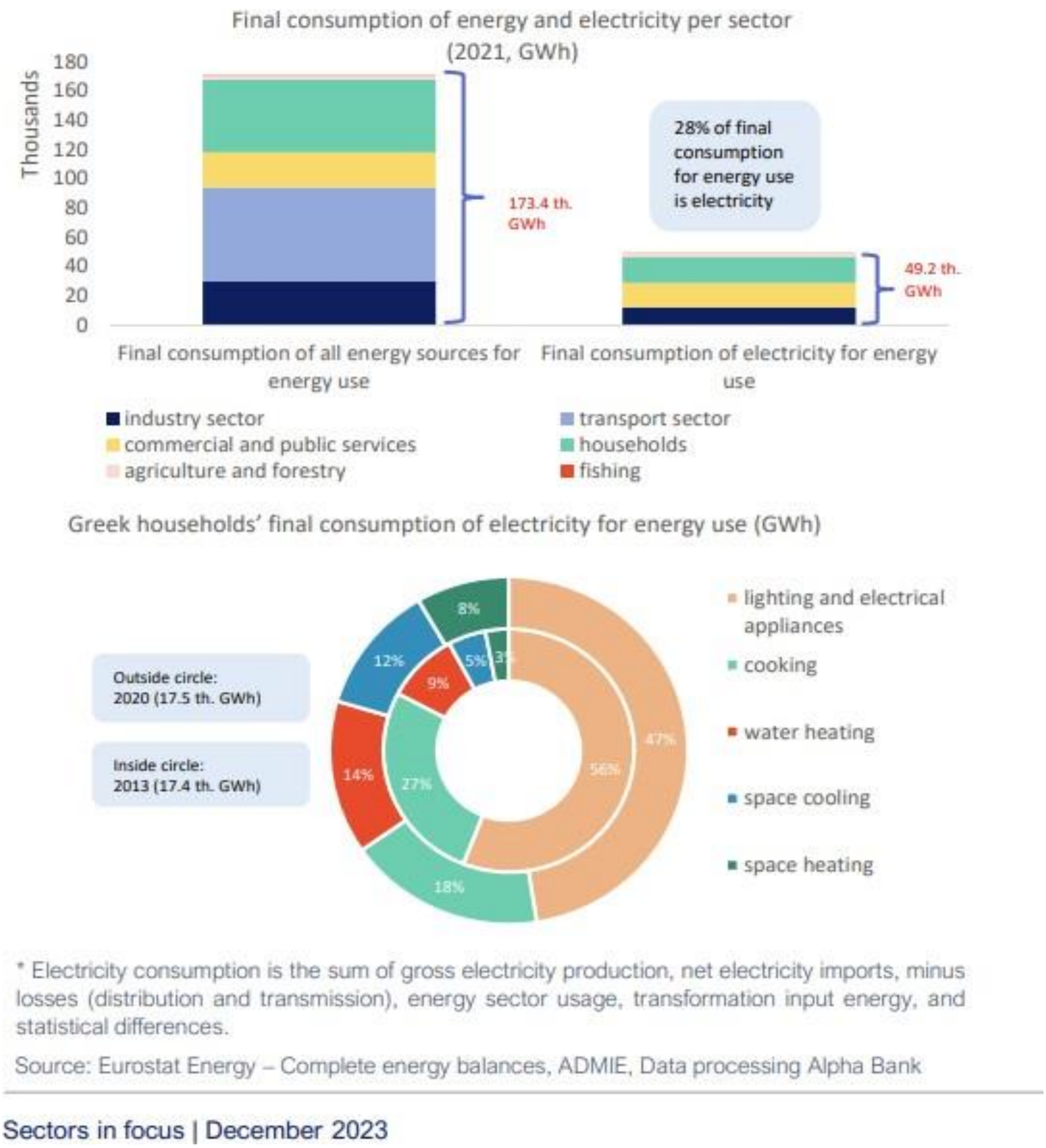


Figure 32: Dr. Kapopoulos E., Dr. Thomaidou F., & Kati S. (2023). Electricity: Renewable Energy Sources and the power landscape in Greece, Alpha Bank - Economic Research Division, alphabankeconomicresearch@alpha.gr

In 2021, electricity comprised 28% (49.2 thousand GWh) of total available final energy consumption, constituting nearly 90% of the gross electricity production. Household consumption was the highest at 36%, followed by commercial and public services (34%), industry (25%), and agriculture/forestry (5%). Notably, non-ferrous metals and food, beverages, and tobacco were the most electricity-intensive manufacturing sectors, contributing 8% and 4%, respectively, in 2021.

For households, lighting and electrical appliances constituted 47% of the 17.5 thousand GWh of electricity consumed in 2020, showing a decrease from 56% in 2013. While overall household consumption remained stable, cooking represented 18% of consumption in 2020, significantly down from 27% in 2013. Water heating and space cooling/heating constituted 35% of household electricity consumption in 2020, doubling since 2013.

Monthly patterns revealed electricity demand peaks during the summer (July and August) due to increased air conditioning usage, followed by winter peaks (December and January) attributed to heightened space heating with air conditioning (IPTO).

2.6.5 Annual Consumption

The graph below shows the evolution of energy consumption by trend for the years 2018-2021.

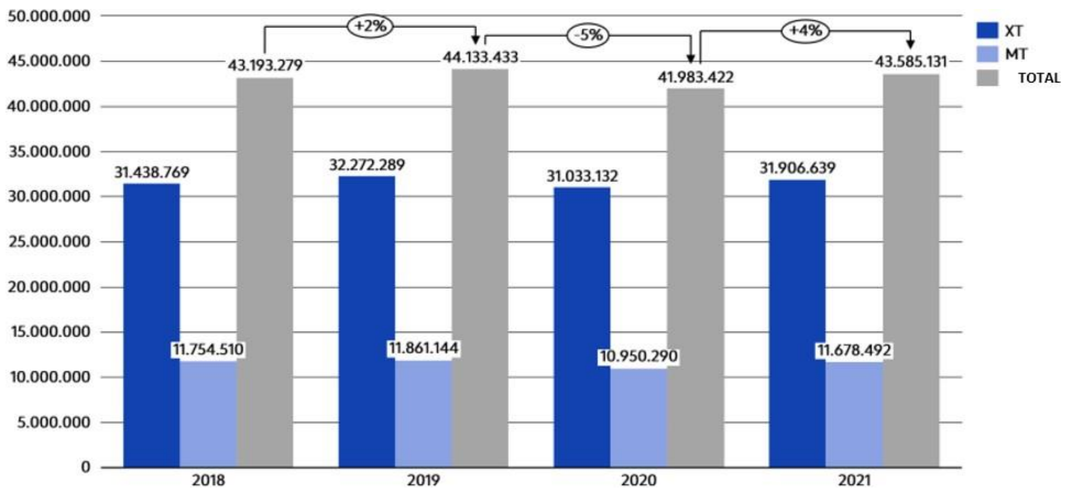


Figure 33: Evolution of Energy Consumption by Voltage Level for the Years 2018-2021 (Source: HEDNO, PPS 2022-2026)

The table below presents the consumption data by voltage level and use for the year 2021 with a distinction for the Board of Directors and for the NII.

Table 7: Annual Energy Consumption (MWh) by voltage and use (31.12.2021) (Source: HEDNO, Distribution Statistics for the Year 2021)

Trends / Uses	IS	NIIs	Total LV
Low Voltage			
Household	15,991,883	1,741,264	17,733,147
Industrial	469,653	38,519	508,172
Commercial	8,629,329	1,465,028	10,094,358
Agricultural	1,788,809	179,773	1,968,582
ΦΟΠ	693,537	70,101	763,637
Publicly	671,126	167,616	838,742
Total LV	28,244,338	3,662,302	31,906,639
Medium Voltage			
Industrial	5,042,223	214,536	5,256,759
Commercial	3,931,612	748,091	4,679,703
Agricultural	426,902	19,543	446,445
Attraction	129,047	0	129,047
Publicly	1,008,724	157,814	1,166,538
Total MT	10,538,509	1,139,983	11,678,492
Total MV and LV	38,782,846	4,802,285	43,585,131

2.6.6 Details of RES Plants

A large number of RES units are connected to EDNO, concerning wind farms, biomass and biogas units, hydroelectric power plants, CHP, PV parks, PV special roofing program or PV net metering program. In summary, at the end of 2021, the capacity of RES in operation amounts to 3,962 MW (MT) and 1,335 MW (XT) in the BoD and 168,335 MW (MT and XT) in the NII. Data regarding the number and capacity of RES units in operation per Administrative Region of HEDNO are presented in the following Tables.

Table 8: RES Stations in Operation by Voltage Level, Technology and Administrative Region of HEDNO (31.12.2021) (Source: HEDNO, PPS 2022-2026)

Administrative Region	Technology	MV		LV		TOTAL	
		Number	Power (MW)	Number	Power (MW)	Number	Power (MW)
Attica Region	Wind Farm	4	30			4	30
	Biogas	7	37			7	37
	Biomass			4	0	4	0
	CEH	11	51	1	0	12	51
	HS	1	1			1	1
	P/V Pannel	341	172	6,325	94	6,666	267
TOTAL ATTICA		364	291	6,330	95	6,694	386
Region of Central Greece	Wind Farm	63	397			63	397
	Biogas	17	16			17	16
	Biomass	5	7			5	7
	CEH	5	10			5	10
	HS	29	53			29	53
	P/V Pannel	1,372	909	8,311	249	9,683	1,158
TOTAL CENTRAL GREECE		1,491	1,392	8,311	249	9,802	1,641
Region of Macedonia-Thrace	Wind Farm	12	80			12	80
	Biogas	35	31	1		36	31
	Biomass	6	4	3		9	4
	CEH	9	28	3		12	28
	HS	58	77	2		60	77
	P/V Pannel	1,411	933	22,455	469	23,866	1,402
TOTAL MACEDONIA-THRACE		1,531	1,153	22,464	469	23,995	1,622
Region of Peloponnese - Epirus	Wind Farm	30	257			30	257
	Biogas	13	8			13	8
	Biomass	6	4			6	4
	CEH	35	99			35	99
	HS	699	520	14,721	409	15,420	930
TOTAL PEL/NISSOS - EPIRUS		783	888	14,721	409	15,504	1,298
Islands Region	Wind Farm	53	233	2		55	233
	Biogas	2	1			2	1
	HS	1				1	
	P/V Pannel	34	4	3,989	113	4,023	116
TOTAL IPN		90	238	3,991	113	4,081	351
TOTAL		4,259	3,962	55,817	1,335	60,076	5,298

Table 9: RES Stations in Operation by Voltage Level, Technology and Administrative Region of HEDNO (31.12.2021) (Source: HEDNO, PPS 2022-2026)

Connection Voltage	Technology	Power (MV)
MT & LV	Wind Farms Small Wind Farms	108,015 0.045
	P/V Pannel	51,450
	Hybrid Systems	2,950
	P/V Net Metering P/V Special Programme	1,180 4,680
	Total	168,335

2.6.7 Distribution Network Control Centers

The management and continuous supervision of the MT Networks and, as the case may be, the HV Network included in EDNO is carried out through the Distribution Network Control Centers (KEDD).

The operation of the KEDS ensures:

- The continuous and smooth flow of electricity from the connection points of EDNO to the HETS or to the NII Power Stations to the consumption points (e.g. Distribution M/S, MT users) and with normal voltage, i.e. keeping the voltage within the acceptable limits, as defined by the applicable Regulations.
- The improvement of the indicators of the quality of the electricity supplied (improvement of SAIDI, SAIFI, CAIDI indices), through remote controls of MT line departure switches, remote controlled switches on the MT network, etc.
- The safety of the facilities and the personnel who deal with them for any reason.
- The improvement of the operation of the Network, through the reduction of operating costs (reduction of man-hours of breakdowns and scheduled outages, etc.)
- The management of the Network by utilizing the data (measurements-markings) drawn from the equipment in the field for the planning of new projects according to the demand assessment, but also the timely detection of any malfunctions that threaten the smooth operation of the Network.
- The rejection of loads for security of supply reasons (e.g. irrigation loads)
- The provision to RAAEY of data related to the operation - exploitation of EDNO.
- The voltage adjustment to within the permissible limits is achieved through the systems for changing the voltage under load on the M/S HV/MT and MT/MT, through

the voltage regulators installed in the MV networks and through the compensation capacitors installed in the HV/MT submarines and MT networks.

2.6.8 Continuity of User Feed

The continuity of user feeds shall be determined by the frequency and duration of power cuts. Power cuts are situations where the voltage at the Network/User limit is less than 5% of its nominal value. The key User Continuity Indicators are presented below.

Power Outages are divided into:

Planned Power Outages, i.e. those that are necessary for the implementation of scheduled works on EDNO and users are informed in a timely and adequate manner before their commencement, as well as those that take place in the context of implementing requests by the Transmission System Operator or users for maintenance works at their facilities

Unplanned Power Outages, which are usually due to errors or failures of Network elements as well as to events outside the sphere of responsibility or control of the Network Operator. It is noted that Unplanned Interruptions are distinguished based on their duration into:

- Long Power Outages, the duration of which exceeds 3 minutes and which are usually caused by permanent faults or failures
- Short Power Failures, the duration of which is less than 3 minutes and which are usually caused by the operation of the means of protection of the overhead parts of the Network (cycle of interruptions-automatic reinforcements, switches, line departures) to isolate transient errors.

Remote meters installed on all MT consumers can be used to monitor the continuity of supply to MT consumers. The local recording by the above meters of power supply interruption events and the transmission of the relevant information to the Telemeter Center of the Operator in combination with other systems or applications can give reliable results.

2.6.9 Emergency Management

According to the EDNO Management Code, an emergency exists in cases where the following have arisen or are expected to arise:

Large-scale power outages, such as:

- General outage (affects all or almost all of EDNO or large NII).
- Interruption of a large local area (larger than a regional unit of the country).

- Interruption of load for a specific period of time, at the discretion of the Network Operator, such as:
- Stop above 50 MVA for more than 30 minutes.
- Stop above 20 MVA for more than 2 hours.
- Stop above 5 MVA for more than 24 hours.
- Interruption of power supply to a medium-sized NII power system or an interconnected island with a capacity of 5 to 100 MVA for more than 30 minutes.
- Interruption of power supply to a small NII power system or an interconnected island with a capacity of up to 5 MVA for more than 60 minutes.
- Interruption of power supply to an island belonging to an NII electrical system and powered via a submarine cable for more than 120 minutes.

Large-scale deviations of the operation characteristics of the Network (voltage, frequency) from their nominal values, extending to extensive geographical areas (regional unit level and above or island level) or affecting the quality of energy provided to a large number of Users (over 5,000).

Emergencies may arise in particular from the following causes:

- Activation of alarm by the System Administrator (IPTO).
- Emergency notification by the NII Administrator.
- Interruption of the operation of important elements of the Network, such as: H/S HV/MT, submarine cable MT.
- Interruption of the operation of an extensive section of the Network, due to its destruction by extreme weather conditions (e.g. heavy snowfall) or by extensive outdoor fires.
- Shutdown of systems important for monitoring and controlling the operation of the Network such as SCADA-DMS systems.
- Incidents that are estimated to lead to exceeding the limits of acceptable operation of Network elements (e.g. malfunction of voltage regulation systems in HV/MT or MT Network).
- Events that cause a significant deviation of the operation characteristics of the Network from their nominal values (e.g. network overload).
- Force majeure incidents (e.g. earthquake, mass mobilizations, interventions by public authorities, sabotage, terrorist acts).
- Unforeseen events (e.g. loss/deregulation of Telecommunication Systems, social reactions, political crises).

Any other case in which the safe operation of the Network is jeopardized at the discretion of the Operator, such as a short circuit to earth, of high resistance. The Operator ensures that all necessary measures are taken to prevent emergencies and limit their consequences. The Table below lists indicative measures for the prevention and suppression of emergency situations taken by HEDNO. More detailed arrangements are provided in the Network Operation Manual, while technical details may be specified in relevant Instructions of the Operator. The Operator, depending on the extent of the emergency, shall ensure that the competent Ministry, the Authorities and the bodies affected by the emergency are informed. In addition, it provides detailed information to RAE on emergency situations, which meet both (2) of the following criteria:

- The number of EDNO users affected by the emergency is over 20,000.
- The duration of the emergency is at least 30 minutes.
- The briefing of RAE takes place in two (2) distinct stages, as follows:
- Within one (1) month from the occurrence of the Emergency State, the Network Operator submits to RAE information on the incident, its causes, its extent (power and downtime) and the corrective actions taken by the Network Operator to mitigate the nuisance of Users until the full restoration of normal electricity.
- Within four (4) months from the submission of the first stage, the Network Operator shall submit to RAE any additional data submitted with the first relevant information, as well as data regarding the costs incurred as well as proposals with timetables of actions for the elimination of similar phenomena in the future.

2.6.10 Network Level Feed Continuity Indicators

For Unplanned Long Power Supply Interruptions, HEDNO uses the following Supply Continuity Indicators at Network Level:

- System Average Interruption Frequency Index (SAIFI).

For Unplanned Short Power Cuts, HEDNO uses the following Supply Continuity Indicators at Network Level:

- Momentary Average Interruption Frequency Index (MAIFI).

2.6.11 User-Level Feed Continuity Indicators

User-level Feed Continuity Indicators are divided into 2 categories:

- User-level Feed Continuity Indicators related to time duration and include the following:
- Maximum permissible time limit of Unplanned Power Interruption at the premises of a User during which the Network Operator has the obligation to restore the power supply.

- Maximum permissible time limit of Planned Power Interruption at the premises of a User during which the Network Operator has the obligation to restore the power supply.
- Currently, the Network Operator has the ability to calculate the above Indicators only for MT.
- Feed Continuity Indicators at MT User level related to frequency and include the following:
- Frequency Index of Unplanned Power Outages, i.e. the annual number of exceedances of the maximum allowed time limit.
- Frequency Index of Planned Power Outages, i.e. the annual number of exceedances of the maximum allowed time limit.

2.6.12 Voltage Quality & Indicators

Voltage quality refers to the set of disturbances that distort the basic characteristics of the voltage of the Distribution Network, i.e. lead to deviations of their characteristics from their nominal value. The basic characteristics of the voltage and their distortion disturbances are defined in Standard EN 50160. Deviations of the basic characteristics of the voltage during the normal operation of the Network are caused due to changes in the load, the operation of equipment of special types and due to errors or disturbances mainly due to exogenous factors. The Voltage Quality Indicators for measuring the deformations of its basic characteristics are:

- Voltage fluctuations: A series of trend changes or a periodic change in the contour of the trend curve.
- Flicker: The visual impression of instability caused by a light stimulus whose brightness or spectral distribution fluctuates with time.
- Phase asymmetry: The state of a three-phase system, in which either the active values between phases or the angles between successive phases differ for any pair of phases.
- Voltage frequency: The disturbance in voltage frequency refers to the deviation of the basic operating voltage frequency of the Network from the foundation (nominal).
- Voltage harmonics: Any sinusoidal voltage with a frequency equal to an integer multiple of the fundamental frequency is called a harmonic voltage. Harmonic stresses can be estimated in total by the Total Harminic Distortion (THD) coefficient.
- Signal voltages: The Distribution Network can also be used for the transmission of signals, such as those related to the switching on and off of municipal lighting or the operation of time zone meters.
- Supply voltage dips: Supply voltage dip is defined as a sudden decrease in the supply voltage to a value between 90% and 5% of the rated voltage, followed by a return of the voltage to the nominal value after a short period of time. The duration of a voltage dip can be from 10 ms to 1 minute. The magnitude of a dip is defined as the difference

between the minimum indicated voltage value during the voltage dip and the rated voltage.

- Surges: Overvoltages are divided into 2 categories:
- Transient, involving short or instantaneous surges with or without oscillation, usually very abrupt and with strong damping.
- Transient (or Incidental), which involve longer lasting surges at a specific location.

HEDNO, is prioritizing the modernization of the electricity distribution network and its transformation to a smart grid. Smart grids use digital technologies to monitor and manage the electricity distribution network. This allows for better network control and can help to reduce outages and improve energy efficiency. The distribution network digitalization is a key priority of the National Energy and Climate Plan. By 2030, digital smart meters will replace conventional ones for all low-voltage consumers and provide real-time data on electricity consumption, used by consumers to better manage their energy use, and by DEDDIE to better manage the network. The network's digitalization via smart grids is supported by the European Investment Bank and Recovery and Resilience Facility loans (DEDDIE, IEA 2023, Greece 2.0 2021). By digitizing the network, Greece can improve its efficiency and reliability, and support the growth of renewable energy.

2.7 Conclusion

Following widely recognised vulnerability/risk assessment methodologies, as well as know-how from international literature and DSOs of other developed countries, an extensive list of adaptation measures has already been developed, a summary of which can be found in the following Tables,

In any case, the development and implementation of a comprehensive Climate Change Action Plan, will require further specialised studies, actions and processes. The results of a Vulnerability Assessment study will guide the more effective prioritisation of appropriate adaptation measures, which, in cooperation with stakeholders, will formulate a corresponding Action Plan. Key to the successful implementation of the Plan, which is expected to be quite demanding in terms of resources, is its incorporation as a structural element in Greece's DSO - HEDNO's 5-year development plan and in the organisation's broader long-term strategy.

Table 10: Summary of Short and Medium-term Adaptation Measures

Support physical system hardening	
Aerial Network	Selective undergrounding of lines in the MV network Gradual and targeted replacement of bare wires by twisted cables in the overhead MV network and universally in the overhead LV network Replacement of bare wires by covered conductors in the MV network Pole densification Reinforcement of wooden poles Replacing wooden poles with concrete ones Relocation of critical infrastructure or vulnerable lines to less vulnerable areas Update of cable specifications, either by improving their characteristics at 50 °C or by redetermining their maximum load Inspection of lightning protection Design of distribution network with increased flexibility Pre-tensioning of conductors.
Underground Network	Replacement of overhead or underground S/S by compact S/S Link-Box with improved specifications Targeted replacement of old cables with XLPE cables.
Substations	Phase out of 22/6.6 kV S/S HV/MV S/S maintenance schedule Fire protection works on 150/20kV S/S and Regional Warehouses Flood protection works for HV/MV S/S at high-risk or with a history of flooding Flood protection works for indoor MV/LV S/S at high-risk or with a history of flooding Net Zero Plan.
Enhance monitoring and controllability in system operation	
Network Digitization	Enhancing network's digitalisation GIS (Geographic Information System) mapping of MV and LV network.
Automation	Modernisation of HV/MV S/S Extension of the installation of remotely controlled elements - enhancement of network intelligence Digitization of Electrical Systems in Non Interconnected Islands Telematics in vehicles.
Corporate Climate Adaptation governance & management practices	
Studies / periodic inspections	Distributed generation – Demand management.
Creation / revision of technical rules, codes and standards	Update of Network Construction Manual Standards Update of guidelines for network design - studies Network inspection – preventive maintenance schedule Update pruning and deforestation guidelines Update of network equipment and material specifications Operational planning for disaster and crisis management Preparedness exercises

	Call Center for Fault Reporting Creation / revision of cooperation networks with equipment suppliers Cooperation with the Greek Army.
Capacity building and knowledge transfer	
	Recruitment of human resources Human resources training on technical issues Training and briefings on Climate Change crisis management Cooperation with third parties.
Financial planning and funding schemes	
	Research & Development Insurance Climate resilience funding program.

Table 11: Summary of Long-term Adaptation Measures

Support physical system hardening	
Hardening of overhead distribution network (where applicable)	Reinforcement of wooden poles by adding brackets to increase lateral stability Replacement of wooden poles by synthetic ones.
ardening of underground distribution network	Filling mixture of underground cable ditches.
Enhance monitoring and controllability in system operation	
Automation	Investigation of new / innovative technologies Information transmission systems and communication.
Corporate Climate Adaptation governance & management practices	
Creation / revision of technical rules, codes and standards	Update pruning and deforestation guidelines Establishment of procedure for preventive interruptions Predictive Maintenance.
Creation / review of coordination groups	Support systems.
Capacity building and knowledge transfer	
	Establishment of a Climate Resilience Task Force.

CHAPTER 3
INVESTMENT FORECASTING, PLANNING, AND IMPLEMENTATION OF MCA ANALYSIS

3.1 Factors for prioritizing investments to enhance the resilience of distribution networks and their adaptation to Climate Change

The optimization of the design of the Distribution Network through the development of a flexible investment cycle is a prerequisite for its required transformation. In this context, the monitoring of the Network in order to identify and anticipate new investment needs for its upgrade in order to improve its reliability and resilience, the appropriate prioritization of investments and the facilitation of their implementation by mitigating administrative obstacles and limiting execution time, etc. pose a great challenge for Administrators.

Investments should be directed towards strengthening networks in order to address congestion and saturation phenomena (e.g. saturations of PCs due to high RES connection in specific sectors), improve their quality characteristics (e.g. control of voltage fluctuations in LV, imbalances between phases, etc.) as well as ensure flexibility with emphasis on RES and storage (Monitor Deloitte, 2021). A crucial component is also the promotion of investments in research and innovation, in particular in technological developments that significantly reduce the cost of renewables and batteries, allow HOs to provide energy to the grid, highlight hydrogen and CO2 capture applications, as well as new uses for infrastructure, such as storing RES in natural gas networks through electrolysis (power-to-gas). The transition time from pilot to large-scale applications and the rate of fall in costs affect the uptake of these technologies.

At the same time, for the implementation of investments, their acceptance by local communities should be ensured. To this end, the active involvement of central and local authorities at national level is necessary (e.g. understanding the source of reactions to each project through informal or formal consultation, participation in consultation/conciliation procedures, acceleration of court decisions, support of local communities with compensatory measures, etc.) to facilitate planned or ongoing projects (interconnection of islands, strengthening electricity grids, RES investments, etc.). Energy communities can facilitate the participation of local communities in the development of RES investments and enhance their social acceptance, but a mechanism is needed to control and prevent possible abuse of the favorable treatment they face (IOBE, 2021).

Indicatively, the factors and selection criteria for prioritizing investments to enhance the resilience of distribution networks and their adaptation to Climate Change could be collected as:

1. Technical characteristics of the Distribution Network - eg. relationship between overhead and underground network at the level of the Area of the HEDNO Region where the investment is made.

2. Historical data on the frequency and duration of power cuts due to extreme weather events expressed through:

(i) the Average Duration of Unplanned Long Power Supply Interruptions Index;

(ii) the Average Frequency Index of Unplanned Long Power Outages due to Supply Interruptions due to extreme weather events per Region and Region.

3. Population and socio-economic factors, such as:

• Number of local residents (and therefore affected consumers)

• Existence of critical infrastructure

• Commercial, tourist and industrial activity of the area

The above criteria significantly affect the degree of operation of each line due to increased load density and should be assessed on a line-by-line basis.

4. Economic impact of supply disruptions from extreme weather events. From the recording of Supply Interruptions, energy not served can be determined for each Region and Region

5. Possibility of implementing preventive maintenance measures (soil morphology, type of area - urban, non-urban, settlement with vegetation). The low capacity to implement these measures is an important criterion for prioritising investments.

6. Vulnerability to Climate Change, specifically to extreme weather events (shocks) and its long-term effects (stresses). Climate vulnerability is assessed at district level.

7. Protection of the natural environment. Priority should be given to areas where investment contributes to environmental protection. Therefore, a criterion that can be used to prioritize the areas under assessment is the protection of protected areas of national legislation (e.g. areas of absolute protection and nature protection, natural parks, habitat and species protection areas, etc.).

8. Investment factors including:

(a) Investment level required

(b) Impact on the final consumer price

The criteria presented for prioritizing the allocation of funds to projects to improve the resilience of distribution networks and their adaptation to Climate Change are mainly based on the axes of sustainable development, environmental and social.

It should be noted that the purpose of this thesis is the presentation and analysis of methodologies and principles that could be used to prioritize utilizing the method of Multicriteria Analysis. Due to limited information in relation to the variable factors that frame and influence the above criteria, the utilization of methods in relation to them, regarding the Energy & Network Management Sector, cannot be occurred at this stage.

Every day, decisions determine the activities and actions of persons in a consistent manner, whether individually or collectively. The relevance of decisions has grown over time, and hence the decision-making process has become more "scientific" (Paraskevopoulos, 2008).

The desired outcome is to select the best solution. That is, this alternative satisfies as many of the criteria and objectives as possible. As such, this is also the nature of choice problems: There is a complex problem that can be addressed through a variety of possible solutions (decisions, policies, activities, or actions). Which of these is the most advantageous is unclear because they have various properties, can provide different results, and may not be comparable using conventional measures. This is why these issues are classified as "complex." As a result, there is virtually no optimal solution, as it may be ideal for some criteria while a better solution exists for others.

A cost-benefit analysis attempts to quantify the monetary value of an option's projected effects. These appraisals are founded on a well-developed economic valuation theory based on willingness to pay or accept. This theory can serve as a guide for achieving valuation and as a referee in valuation disputes. The valuations are based on possible gainers' willingness to pay for the benefits they would obtain as a result of the option, and potential losers' willingness to take compensation for the losses they will incur. In general, a project is desirable if the benefits outweigh the losses, which have been appropriately discounted over time. Because compensation is rarely given, there will be both winners and losers. This is known as the potential compensation concept. Because desire to pay and willingness to accept will be affected by income distribution, there may be a rationale for weighting profits and losses to account for income distribution.

In fact, valuing all of the costs and advantages of options in monetary terms is rarely feasible. Most cost-benefit evaluations will include some additional items that are either impossible to value or uneconomic to value. However, after the most essential costs and benefits have been determined, the others can be considered alongside and included in the decision-making process. As a tool for guiding public policy, CBA offers many advantages:

- It takes into account the profits and losses to all members of society on whose behalf the CBA is being conducted.
- It evaluates impacts in terms of a single, well-known measurement scale - money - and can thus demonstrate that implementing an option is advantageous in comparison to doing nothing.
- The monetary values used to weigh the relative relevance of the various impacts are based on people's preferences, which are normally measured using recognized procedures.

While processes such as stated preference or hedonic pricing can be used to generate monetary values for some non-marketed outcomes, it is not always possible. Relevant data may be unavailable or prohibitively expensive to gather. Some effects may be impossible to present in language where individuals can make reliable trade-offs against money. Furthermore, there may be consequences that cannot be easily defined and compared to a monetary scale. CBA is also occasionally chastised for the weakness that it does not generally take into consideration the interplay between different affects.

All cost-benefit analyses include elements that have been identified as relevant affects but are not valued. They may be viewed as modest in some cases, and hence will be reported in the CBA report with the overall estimates of those net social benefits that can be valued. They may strengthen the choice ordering given by monetary outcomes, or they may not be considered as adequate to shift this ordering, or they may tip the balance in cases where the difference between alternatives implied by monetary valuations is modest. In other cases, however, there may be things for which appropriate values have not been determined but which are nonetheless viewed as critical. MCA approaches may be effective in certain situations.

Much more severe is the fact that, while techniques such as stated preference or hedonic pricing allow for the establishment of money values for some non-marketed outcomes, it is not immediately possible for others. Relevant data may be unavailable or prohibitively expensive to gather. Some effects may be impossible to present in language where individuals can make reliable trade-offs against money.

Furthermore, there may be consequences that cannot be easily defined and compared to a monetary scale. The number of deaths or injuries avoided by a safety improvement, or the time saved by an investment in public transportation, can usually be properly quantified and valued against a predetermined monetary scale. A unique research may also be able to determine the value of a given environmental cost or improvement to individuals who would be affected. However, the implications of a proposed government measure on outputs with diffuse societal consequences, such as social cohesion, are frequently matters on which Ministers want to express their opinions at the time of decision.

CBA is also occasionally chastised for the weakness that it does not generally take into consideration the interplay between different affects. People may be more negatively affected by a project that imposes both environmental and social costs than would be predicted by adding independent estimates of the two effects.

More broadly, anytime certain costs and benefits may be valued in monetary terms, either directly by price observation if appropriate or indirectly through commonly acknowledged procedures, these data should be used within any larger MCA. As we will see throughout the manual, MCA applications frequently require the combination of some criteria that have monetary values and others that do not. Difficulties arise when some of the monetary valuations are deemed to be weak. More resources may be used in the long term to try to improve their accuracy, but in the short term, appraisers may consider using sensitivity analysis to see how much results depend on the specific values used, or whether it might be more appropriate to ignore the (rather mistrusted) monetary values and rely on some more subjective scoring and weighing systems to reflect decision makers' or interest groups' preferences.

According to Dr. Dean's "Practical Guide to Multi-Criteria Analysis," MCA can, in theory, provide better insight into the nature of the problem at hand and finally lead to more thorough judgments when compared to mono-criterion appraisal and evaluation methodologies. However, as he points out in his research, both formal and reduced MCA techniques have logical problems and inconsistencies. Making more informed decisions is dependent, among other things, on the breadth of the value tree of objectives and criteria addressed in the analysis. It is difficult to choose a balanced and complete set of objectives and criteria.

Given the lack of precise and universally agreed-upon recommendations in the MCA literature on how to construct these parameters, two separate analysts (or two different teams of analysts) confronted with the same multi-criteria problem are quite likely to yield two conflicting value trees. The creation of a list of objectives raises the tough question of what perspective to use and what interests to consider in the appraisal or evaluation process.

Indeed, whereas the goal of CBA is to estimate the potential social surplus generated by a project or policy action by attempting to account for the consequences felt by all members of society, the scope of MCA is less obvious (Dean, 2020; Mouter et al., 2020). On the one hand, the MCA literature emphasizes the importance of adequately representing all parties involved in or affected by the problem situation under consideration (e.g., Dodgson et al., 2009; Dimitriou et al., 2010; Macharis and Nijkamp, 2011; Macharis and Bernardini, 2015). On the opposite end of the spectrum, for major policy decisions with far-reaching implications in both space and time, identifying all potential stakeholders and their agendas is difficult, and in many cases is made even more difficult by time and budget constraints to conduct the analysis. As a result, in selecting a set of relevant objectives to account for the potential impacts of the options under consideration, analysts are likely to adopt (implicitly or explicitly) the client perspective (e.g., the Minister, Government Department, project promoter, agency, or group that commissioned the analysis) and/or take primarily into account (intentionally or unintentionally) the positions of only a few stakeholder groups (i.e., typically the most organized, and oft-cited This may raise serious concerns about equity (Dean, 2018).

Furthermore, while MCA allows for the evaluation of choices against a wide range of quantitative and qualitative objectives in theory, in fact, the performance of options against many of these criteria can be difficult to quantify or evaluate. These 'intangible' and'soft' qualities, such as equity, cohesion, happiness, quality of life, and sense of place, can be difficult to objectively describe and convert into concrete metrics (Miller, 1985; Vanclay, 1999; Anciaes and Jones, 2020). Given the high level of ambiguity surrounding appraisal and assessment studies, it may be able to acquire only rough and hazy data and information about the performance of the options under consideration for various criteria. For other factors, the information search method may be deemed too time-consuming, complicated, or costly. Finally, the required data and information for some other criterion may just not exist16 (Dom, 1999; Gustavson et al., 1999). As a result, even for MCA activities that begin with the creation of broad value trees including a wide range of features, values, and interests, the final assessment may be based on only a few objectives and criteria.

Finally, Dr. Dean concludes that, in comparison to other appraisal and evaluation methods, in many MCA applications, objectives and criteria are frequently selected with little regard for the geographical and temporal dimensions of the analysis. As a result, especially in simplified MCA techniques, the performances of choices against the various criteria risk becoming essentially a collection of snapshots, with no common (spatial or temporal) basis for comparison.

3.1.1 Methodological framework of multicriteria decision analysis

Multicriteria analysis, according to Roy (1996), should clarify the competitive character of the criteria, model the decision-maker's preferences, and suggest satisfactory solutions. Roy's proposed broad methodological framework is divided into four stages:

- All alternative actions and the problem of analysis are defined in the first step. 'Alternative' is defined as any feasible solution to a problem that will be examined for acceptability (Spanos, 2004). Following that, the choice problem must be defined. There are four problems that encompass practical cases in general (Roy, 1996):

1. A problem's type refers to the selection of one or more solutions that are thought to be the most acceptable (choice).
2. Problem b is about categorizing alternatives into preset homogeneous groups (classification/sorting).
3. The problem c is about ranking alternative activities from excellent to worst (ranking).
4. The description of alternatives based on individual evaluation criteria is referred to as problem d.

- Criteria are defined in the second step of the problem analysis process. The alternatives' performance against the chosen criteria will be used to evaluate them. The decision-makers define the criteria after considering the objectives that each policy-alternative picked must meet.
- The third stage defines how to establish the criteria on which the problem's subject (selection, categorization, classification, description) will be composed, as defined in the first stage. In other words, the mathematical synthesis of all criteria is performed based on the problem selected in order to complete the analysis's purpose. The model is used to: determine an overall evaluation of each alternative, make bilateral comparisons between alternatives, and grow the number of alternatives (in a continuous set) (Spanos, 2004).
- The model is applied and results are extracted in the fourth and final stage of the procedure. All activities that will assist the decision-maker in understanding the findings of the criterion synthesis model developed in the third stage, as well as the process by which these results were retrieved, take place here (Paraskevopoulos, 2008).

In essence, this stage is the completion of the third stage, but it serves a purpose because a solution that provides a model does not guarantee that it will be directly exploitable in decision-making sectors. It is ultimately the decision-makers' judgment and flexibility that will choose the best appropriate policy, most commonly following a logic based on the composition of the criteria outlined in the third stage.

Roy (1985) recommended categorizing models into three categories based on their format:

- One-of-a-kind synthesis criterion approaches that ignore any incompatibility between alternative activities.
- Outranking the synthesis strategy, notwithstanding the possibility of non-comparability across alternative activities.
- A local judgment technique that is interactive. Pardalos et al. (1995) offered an alternate grouping of multicriteria techniques.

This classification considers not just the format of the models generated, but also how they are developed. This classification contains the four categories listed below:

- Multiobjective mathematical programming,
- Multiattribute utility theory,
- Theory of outranking relations,
- Analytical-synthetic approach (preference disaggregation approach).

Multicriteria mathematical programming is a generalization of mathematical programming theory that is used to maximize multiple objective functions (Paraskevopoulos, 2008). The last three of the four techniques discussed above are geared toward tackling specific decision-making issues. Their goal is to synthesize all criteria in order to evaluate a finite collection of alternative activities based on selection, classification, or classification difficulties.

3.1.2 Key Elements of Multi-Criteria Analysis

Nowadays, the bulk of decisions and problems we confront are of this type, and so optimization as a method is insufficient because there are multiple criteria to satisfy. Addressing these issues entails introducing (selecting) criteria that must objectively reflect the objectives of the problem's alternatives.

The procedure for making the best decision is known as MultiCriteria Analysis (MCA). The importance of the criterion is determined by the decision-makers. The MCA process has a substantial benefit over decision-maker judgment because it takes into account all of the aspects that have been chosen to be investigated concurrently and serves as a medium of communication between decision-makers and stakeholders (Spanos, 2004). Multi-criteria analysis develops preferences amongst choices by referring to an explicit set of objectives stated by the decision-making body and for which quantifiable criteria have been established to assess the extent to which the objectives have been met. In basic cases, the act of setting objectives and criteria may be sufficient to supply decision-makers with sufficient information. However, where a level of detail like to CBA is necessary, MCA provides numerous techniques of aggregating data on individual criteria to create indicators of overall option performance.

The reliance on the decision-making team's judgment in formulating objectives and criteria, assessing relative importance weights, and, to some extent, judging the contribution of each choice to each performance criterion is a major characteristic of MCA. The subjectivity that pervades this can be concerning. Its foundation, in essence, is the decision makers' own selection of objectives, criteria, weights, and judgments of achievement of the objectives, while 'objective' data such as observed prices can also be used. MCA, on the other hand, may add a level of structure, analysis, and openness to decision classes that CBA cannot.

One shortcoming of MCA is that it cannot demonstrate that a particular activity adds more to welfare than it subtracts. In contrast to CBA, there is no explicit logic or necessity for a Pareto Improvement rule requiring benefits to surpass costs. Thus, in MCA, as in cost-effectiveness analysis, the 'best' option may be inconsistent with boosting welfare, so doing nothing may be desirable in principle.

There are several MCA approaches, as evidenced by a vast literature, and the number is continually growing. There are various causes for this:

• There are numerous decision types that match the broad situations of MCA.

• The amount of time available to do the analysis may vary.

• The quantity and type of data available to assist the analysis may differ.

• The analytical capabilities of individuals supporting the choice may differ.

• Administrative culture and organizational requirements may differ.

Some types of MCA do not now provide much assistance in actual decision making, but others can be quite useful. This guidebook defines and explains these practical procedures, as well as the various applications in which they can be applied.

All MCA techniques explicitly state the possibilities and their contributions to the various criteria, and all demand the application of judgment. They differ in how they aggregate the data, however. For the various criteria, formal MCA approaches often include an explicit relative weighting system16. The approaches' principal purpose is to address the challenges that human decision-makers have been demonstrated to have in reliably managing vast amounts of complex information.

A performance matrix, or consequence table, is a standard component of multi-criteria analysis in which each row represents an option and each column describes the performance of the choices against each criterion. Individual performance evaluations are frequently numerical, but they can also be expressed as 'bullet point' scores or color coding. This performance matrix may be the final outcome of the analysis in a basic form of MCA. The decision makers are then tasked with determining how well the entries in the matrix meet their objectives. Such intuitive data processing can be quick and productive, but it can also lead to the usage of unwarranted assumptions, resulting in inaccurate choice ranking.MCA approaches generally employ two steps of numerical analysis on a performance matrix:

1. Scoring: For each criterion, the projected effects of each alternative are awarded a numerical score on a strength of preference scale. On the scale, more favored options score higher, while less preferred options score lower. Scales ranging from 0 to 100 are commonly employed in practice, with 0 representing a real or hypothetical least favored alternative and 100 representing a real or hypothetical most preferred one. The MCA would then analyze all choices between 0 and 100.

2. Weighting: For each criterion, numerical weights are applied to determine the relative valuations of a change towards the top and bottom of the selected range.

Mathematical routines, which may be implemented into computer programs, then integrate these two components to provide an overall evaluation of each alternative under consideration. As a result, this strategy needs persons to offer the inputs that they are most prepared to provide, while leaving computers to handle complex information in a way that is compatible with the preferences revealed by these human inputs. Because low scores on one criterion may be compensated by good scores on another, these approaches are generally referred to as compensatory MCA procedures. The most frequent method for combining criteria scores and relevant weights between criteria is to compute a simple weighted average of scores. This manual's description of MCA approaches with specified weights focuses on such basic weighted averages. The application of such weighted averages is predicated on the premise of reciprocal independence of preferences. This indicates that an option's judged strength of choice on one criterion is independent of its judged strength of preference on another.

3.1.3 Different types of MCA

As previously said, there are numerous MCA techniques. In any case, it will be essential to conduct a brief study of the area as a whole, as different methods may be found in other applications from time to time. The amount of choices to be evaluated is an important first consideration in selecting an MCA technique. Some challenges, particularly in design and engineering, are concerned with infinitely variable outcomes. However, the majority of policy decisions, even at the lowest levels, are usually about choosing between discrete options, such as alternate investment projects or alternative types of tax systems.

When the number of possibilities is limited, it makes no difference whether the number is small or high. It is vital to remember, however, that each alternative that must be considered must be evaluated to determine how well it performs on each of its criteria. The collection and processing of these data will cost resources, especially if a significant number of criteria have been specified. This is an important consideration when deciding whether to apply one of the simpler or more comprehensive MCA decision support techniques. MCA processes are distinguished primarily by how they process the basic information in the performance matrix. Different circumstances will be better suited to some MCA procedures than others.

3.1.4 Direct analysis of the performance matrix

Direct inspection of the performance matrix yields only a limited amount of information regarding the relative merits of choices. An starting approach could be to determine which possibilities are dominated by others. Dominance happens when one option performs at least as well as another on all criteria and is clearly superior on at least one. In theory, one option could trump all others, but in fact, this is improbable. When this happens, it's a good idea to inquire if there's any advantage to the dominating choice that isn't represented by the criteria; this may uncover new criteria that were previously neglected. Dominance is more likely to be used simply to allow the decision-making team to exclude dominated possibilities from further consideration.

After any dominance analysis is completed, the decision-making team must assess whether trade-offs between multiple criteria are acceptable, such that excellent performance on one criterion can in theory compensate for poor performance on another. Most public decisions allow for such trade-offs, but there may be other cases, maybe when ethical problems are prominent, where such trade-offs are not acceptable. If considering trade-offs between criteria is not acceptable, there are only a few non-compensatory MCA strategies accessible. Where compensation is permitted, most MCA approaches require the implicit or explicit aggregate of each choice's performance across all criteria to generate an overall assessment of each option, which may then be compared to the set of options. The primary distinction between the various families of MCA approaches is how this aggregation is accomplished. The sections that follow provide an overview of some of the more well-known techniques.

3.1.5 Methods

The MCA literature contains a large variety of approaches (and versions of these methods) that account for numerous objectives and decision criteria. Despontin and colleagues (1983) conducted a review in the 1980s and discovered more than 100 different MCA techniques. Although these strategies can differ significantly, many of them share basic characteristics and share a decision-support framework that contains the following critical elements:

- **Option:** a proposed alternative course of action to address a perceived problem and accomplish an overall result.
- **Objective:** a specified goal against which any offered option is evaluated. Typically, objectives are organized around various broad appraisal and evaluation factors (for example, sustainability policy concerns typically involve economic, environmental, and social dimensions). Objectives are sometimes classified based on their geographic scope (e.g., local, regional, national, and supranational objectives) and temporal dimension (e.g., short-, medium-, and long-term objectives) (Voogd, 1983). Finally, particularly in interactive MCA exercises, objectives might be aggregated according on the social groupings to which they apply.
- **Criterion:** a precise measurable indicator of an option's performance in relation to a target, allowing measurement of the extent to which an option satisfies that aim. For example, the goal of 'supporting economic growth' can be quantified using a criterion like the 'GDP growth rate' (see Table 1). In theory, each aim can imply numerous different criteria. Another relevant criterion for evaluating growth maximization is real individual consumption per capita. There is a distinction between quantitative indicators, which measure the performance of an option statistically (e.g., monetary units or bio-physical units), and qualitative indicators, which offer a (qualitative) description of the option's performance. Qualitative criteria are often more subjective than quantitative criteria because the former indications are mostly reliant on the participants' personal feelings, opinions, and attitudes.
- **Performance Score:** a pure number (with no physical meaning) that corresponds to a certain scale (e.g., a 0 to 1 scale, a 1 to 100 scale, or a -5 to +5 scale) that identifies an option's performance against a specified objective/criterion. High-performing options receive high ratings, while low-performing options receive lower ratings. Critical objectives and criteria can also be given limitations in the form of precise threshold values, which limit the worst acceptable performance of an option against those criteria. Threshold values can be established in accordance with policy objectives and legal instruments, scientific criteria identifying the limits of natural processes and systems, or ethical norms.
- **Criterion Weight:** a coefficient that is usually used to describe the amount of relevance of an objective and associated criterion in comparison to the other objectives and criteria under consideration (high-priority objectives and criteria are identified with high weights). Still, the real meaning of weights might vary significantly depending on the MCA method used (Munda, 2008; Bouyssou et al., 2000; Belton and Stewart,

> 2002). In a multi-criteria decision-making dilemma, one or more policy (or project) alternatives are often evaluated against a set of criteria for several different objectives. Scores are used to identify an option's performance against multiple objectives and criteria, which might be ascribed different weights. Overall, a multi-criteria technique is defined by the collection of rules that establish the nature of options, objectives, criteria, scores, and weights, as well as how objectives/criteria, scores, and weights are used to analyze, compare, filter in/out, or rank options.

MCA approaches can be used to discover a single most favored choice, to rank options, to shortlist a limited number of options for further extensive evaluation, or simply to discriminate between acceptable and unacceptable possibilities. However, it is neither essential nor desirable to thoroughly investigate any of these strategies. Some are geared toward difficulties that public-sector decision-makers are unlikely to face; others are complex and unproven in practice; and still others lack solid theoretical foundations.

Considering the wide range of MCA methods established over the years, identifying a comprehensive classification scheme, mapping all existing methodologies, and methodically capturing their similarities and differences remains difficult. Several (partial) taxonomies have been proposed over time (e.g., Roy, 1996; Munda, 1995; Janssen and Munda, 1999; Rogers et al., 2000; Belton and Stewart, 2002; Kodikara, 2008; Rogers and Duffy, 2012; Ishizaka and Nemery, 2013; Zardari et al., 2015).

The assignment (or non-assignment) of a method to a certain category within a given categorization system is not always evident and can easily become the subject of a heated debate among experts. Dean's (2018 and 2020) classification, as demonstrated in the image below, is very useful for this paper. The first fundamental distinction addressed by this classification approach is between formal and simplified procedures. Formal MCA approaches are based on sophisticated procedures, certain fairly strict (albeit frequently arbitrary) criteria, and, in some cases, advanced mathematical ideas. Computer assistance is frequently required to implement such procedures, which are nonetheless prone to mistakes and errors.

Many textbooks and manuals that are not easily readable and understandable by general readers (e.g., Chankong and Haimes, 1983; Vincke, 1992; Roy, 1996; Triantaphyllou, 2000; Belton and Stewart, 2002; Figueira et al., 2005b; Bouyssou et al., 2006; Ishizaka and Nemery, 2013) provide a comprehensive examination of formal MCA methods. Simplified techniques, on the other hand (given in Section 3.2), entail simple and frequently rough MCA applications. Despite the fact that the wide range of techniques may be viewed as a strength of MCA, this'methodological anarchy' frequently leads to numerous important difficulties.

When it comes to analyzing and presenting data and information, each method has its own qualities as well as advantages and disadvantages. As a result, finding a suitable MCA approach can turn out to be a multi-criteria challenge in and of itself (Triantphyllou and Mann, 1989). While the choice of which technique to use in a decision-making situation should be adequately justified, this is rarely done in practice. The choice of an MCA method is typically made arbitrarily and is motivated solely by the analysts' and decision-makers' knowledge of a given method, the availability of software and tools for carrying out the analysis, or the existence of examples and similar studies that can be easily replicated.

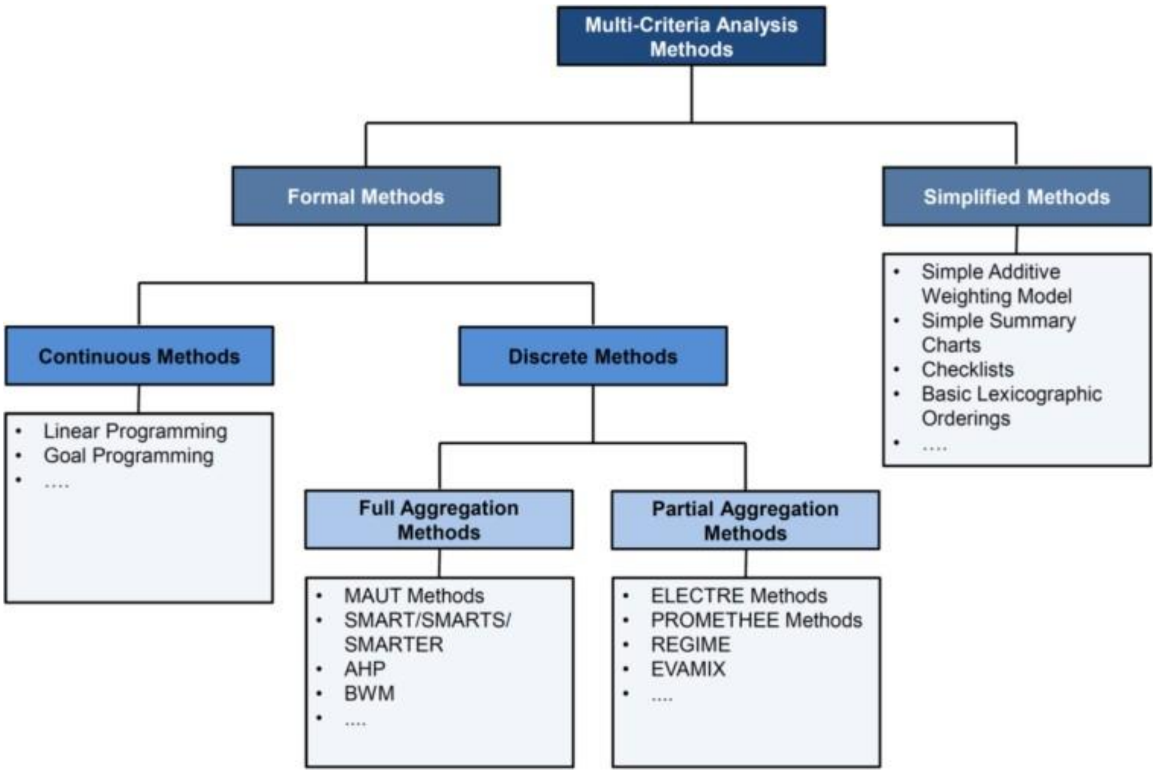


Figure 34: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In *Technical Report*. https://doi.org/10.13140/RG.2.2.15007.02722

3.1.6 Formal Methods

1. Continuous Methods:

These are classified as continuous or discrete methods. Continuous MCA approaches are often used to solve issues when there are an infinite (or extremely huge) number of alternative solutions that are not explicitly known at the outset. This category includes multi-objective programming methods such as linear programming and goal programming, which generate alternatives while solving complex equation systems with an infinite or semi-infinite number of variables, constraints, and objectives (Charnes and Cooper, 1977; Korhonen, 2005; Ehrgott, 2005). Such methods are generally appropriate for technical design and optimization problems (e.g., determining the best highway alignment, selecting the most convenient layout for a port or airport, and traffic signal optimization studies), which typically follow higher-level strategic decisions (e.g., whether or not to build a highway, port, or airport), and can be mastered only by mathematicians and experts.

2. Full Aggregation Methods:

In comparison, discrete approaches better reflect real-world planning and policy challenges when the alternatives to evaluate are restricted in number and reasonably well-defined at the start of the study. The vast majority of formal, discrete MCA approaches can be divided into two broad categories: complete aggregation methods and partial aggregation methods, which reflect two opposing schools of thinking. The former category, which corresponds to the American MCA school, tries to combine an option's performance across all categories into a single, global score. Discrete, full aggregation MCA methods include, among other things, Multi-Attribute Utility Theory (MAUT) methods, the goal of which is to determine the overall utility of an option under study with reference to a given number of decision criteria, which are referred to as 'attributes' here (Keeney and Raiffa, 1976).

Similarly to CBA, the concept of 'utility' reflects a decisionmaker's level of pleasure with a specific outcome with MAUT methodologies (Fishburn, 1970). Each criterion (attribute) has its own utility function, which reflects variable levels of satisfaction based on how an option performs against that specific criterion. MAUT approaches integrate all of the marginal (or partial) utility functions for the separate criteria into a single mathematical expression called the multi-attribute utility function, which represents the overall utility (i.e. the global attractiveness) of that choice. When comparing two or more alternative courses of action using MAUT techniques, the favored option is the one with the highest total utility value. Depending on the nature of the problem and the sorts of criteria included in the analysis, the multi-attribute utility function might take several shapes. In the most basic scenario, it takes the shape of a linear function, allowing the overall utility of an option to be determined as a weighted sum of the utility functions for each individual criterion. In other words, given an option a and a set of N appraisal criteria, the overall utility U of a, as judged against the N criteria, is computed as follows (Dean, 2022):

$$U(a) = \sum_{j=1}^{N} w_j \times u_j(a) = w_1 \times u_1(a) + w_2 \times u_2(a) + \ldots + w_N \times u_N(a) \quad (1)$$

$$\sum_{j=1}^{N} w_j = 1 \quad \text{and} \quad 0 \leq w_j \leq 1$$

Where:
uj (a) represents the partial utility function for the j-th criterion, expressing the performance (utility) of option a on the j-th criterion;

wj is the weight of the j-th criterion, through which uj(a) is scaled to a [0-1] interval.

The single-criterion value functions uj(a) are commonly stated on a 0 to 1 interval scale, with 0 indicating the poorest and 1 indicating the highest possible performance. Given that the criterion weights have values ranging from 0 to 1, the multi-attribute utility function U(a) also has values ranging from 0 (worst utility) to 1 (best utility).
This weighted additive model is only viable if each criterion's utility is independent of the others (Keeney and Raiffa, 1976). This quality, known as'mutual preferential independence,' implies the absence of synergy or conflict between multiple criteria, allowing the marginal contribution of each criterion to the overall value to be evaluated individually. To reduce the probability of such interactions occurring, criteria must be carefully specified and a large number of conditional clauses must be verified (Keeney, 1977).

When mutual preference independence between criteria is not established, the multi-attribute utility function, which combines the multiple partial utility functions, takes on increasingly complex forms (Keeney and Raiffa, 1976; Zeleny, 1982). Some of these types (for example, quasi-additive, multiplicative, quasi-pyramid, semi-cubic, and multi-linear utility functions) with lower independence conditions between criteria are shown in the table below.

According to Zeleny (1982), the only workable models for scenarios with more than four criteria are those with additive or multiplicative utility functions.

Types Of Multi-Attribute Utility Function	Three-Criterion Representations
Weighted Additive Model	$U(a) = w_1u_1(a) + w_2u_2(a) + w_3u_3(a)$
Multiplicative Model	$U(a) = w_1u_1(a) + w_2u_2(a) + w_3u_3(a) + kw_1w_2u_1(a)u_2(a) + kw_1w_3u_1(a)u_3(a) + kw_2w_3u_2(a)u_3(a) + k^2w_1w_2w_3u_1(a)u_2(a)u_3(a)$ With *k* scaling factor
Quasi-Additive Model	$U(a) = w_1u_1(a) + w_2u_2(a) + w_3u_3(a) + w_{12}u_1(a)u_2(a) + w_{13}u_1(a)u_3(a) + w_{23}u_2(a)u_3(a) + w_{123}u_1(a)u_2(a)u_3(a)$
Bilateral Model	$U(a) = w_1u_1(a) + w_2u_2(a) + w_3u_3(a) + w_{12}f_1(a)f_2(a) + w_{13}f_1(a)f_3(a) + w_{23}f_2(a)f_3(a) + w_{123}f_1(a)f_2(a)f_3(a)$ With $f_i(a)$ normalised utility difference functions
Quasi-pyramid Model	$U(a) = w_1u_1(a) + w_2u_2(a) + w_3u_3(a) + w_{12}u_{12}(a) + w_{13}u_{13}(a) + w_{23}u_{23}(a) + w_{123}u_1(a)u_2(a)u_3(a)$
Semi-cubic Model	$U(a) = w_1u_1(a) + w_2u_2(a) + w_3u_3(a) + w_{12}u_{12}(a) + w_{13}u_{13}(a) + w_{23}u_{23}(a) + w_{123}f_1(a)f_2(a)f_3(a)$ With $f_i(a)$ normalised utility difference functions
Multi-linear Model	$U(a) = w_1u_1(a) + w_2u_2(a) + w_3u_3(a) + w_{12}w_1w_2u_1(a)u_2(a) + w_{13}w_1w_3u_1(a)u_3(a) + w_{23}w_2w_3u_2(a)u_3(a) + w_{123}w_1w_2w_3u_1(a)u_2(a)u_3(a)$

Figure 35: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In *Technical Report*. https://doi.org/10.13140/RG.2.2.15007.02722 - Adapted from Zeleny (1982).

Analytic Hierarchical Process (AHP): As a result, the Analytic Hierarchic Process (AHP) prioritizes options by assigning significance weights to the criteria that have been stated. For the hierarchy of options, binary comparisons are conducted based on decision-makers' assessments, and they are synthesised to identify which variable has the highest priority/influence on the outcome (Spanos, 2004). For each criterion, a table of weights and a table of estimates (results) are created. Thomas Saaty (1980) invented the method in response to a shortage of common, readily understood, and practical procedures in the process of making difficult decisions, and it has been widely used ever since. The rationale for this is that it facilitates problem organization and complexity structure, measurement, and ranking synthesis (Spanos, 2004). The approach is recommended for issues with discrete options and is popular due to its ease of usage.

The method basically determines preferences in order to prioritize alternatives. It derives the weights of the criteria by using pair comparisons between criteria and alternatives (Saaty, 1980). As a result, the decision-maker is asked a sequence of questions, each of which asks how essential one criterion is in relation to another in making the decision.

Experts or decision-makers collect data on the hierarchy of objectives in order to compare objectives on a qualitative scale (Gallios, 2009). Decision makers can classify the comparison as "equal," "marginally strong," "very strong," or "too strong."
The values range from 1 (equal importance) to 9 (much more important) or are complementary, i.e. from 1/1 to 1/9. The values that can be offered are as follows: 1, 2, 3, 4, 5, 6, 7, 8, 9 and 1/1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9 (Saaty, 1980).

The Table below shows the scoring options described, as given to decision makers:

Comparative Importance of Preferences		
1	Of equal importance	The criteria have an equally important impact on the problem
3	Slightly more important	Experience and judgment slightly favor the importance of one criterion over the other
5	Much more important	There is considerable evidence that one criterion takes precedence over the other
7	Very important	There is very strong evidence that one criterion is superior to the other
9	Extremely important	There is very strong evidence that one criterion is superior to the other
2-4-6-8		Intermediate Prices

Figure 36: Source: Gaitanaros Dimitrios. (2017). "Applications of different Multicriteria Analysis methods for Water Resources Management: The case of the Lake Karla basin".

The usage of this scoring method is the primary reason for its acceptability and broad use. Its simplicity, as well as the fact that it develops linkages between criteria and alternatives based on DM preferences, which can be articulated in phrases or in conventional English (Gallios, 2009). Using a certain scale, these statements give way to weight-numbers (Saaty, 1990). However, the method has received some harsh technical criticism, including the lack of a formal basis for the scale employed to translate qualitative concepts into numerical values (Saaty, 1980). The occurrence of ranking reversal has raised particular worry (Saaty, 2003). This is the possibility of reversing the ranking of two other options unrelated to the new one by simply adding another option to the list of projected options. Many consider this as incompatible with logical option evaluation and hence calls into question the theoretical basis of the AHP (Gallios, 2009). The AHP method, according to Saaty (1980), is theoretically based on four axioms:

- For a criterion/sub-criterion based on an inverse scale ij=1/ ij, the decision-maker may give pairwise comparisons of aij of two possibilities i and j.
- The decision-maker shall never assess one choice to be clearly superior to another in terms of a criterion, such as aj.
- The decision problem can be organized hierarchically.
- A hierarchy is used to represent all criteria/sub-criteria that have some influence on the current problem, as well as all connected options.

More specifically, the above axioms apply as follows:

After specifying the criteria for evaluating the various options, the procedure begins with a square array with the identical criteria in columns and rows. Each "cell" of the table is the outcome of a comparison of the criteria with the previously discussed scale. Because they are compared to themselves, the diagonal elements will obviously have the value 1.

The eigenvector is then determined, either using software or by following its precise calculation technique. This is followed by another weighing of the alternatives based on criterion comparisons. At the end of the procedure, each criterion and alternative will have a value (or weight). The weight of the related criterion is then multiplied by the value of each choice. Finally, all of the values for an alternative are totaled together.

Alternatives are ranked in order of suitability, in descending order of the obtained prices. Based on the foregoing and Saaty's axioms, Nauman (1998) concludes that AHP is a means of breaking down a problem into a hierarchy of sub-problems that may be better understood and evaluated. The estimates below are transformed into numerical values and used to rate each possibility on a numerical scale. According to Spanos (2004), three essential ideas govern the AHP approach, generalizing the conclusions of the theoretical underpinning of the method:

- The AHP is analytical.
- The mathematical and logical justification for decision-making is the strong feature of the method.
- It helps to analyze the problem on a logical basis and to transform the thoughts and intuitions of the decision maker into numbers.
- AHP structures the problem into a hierarchy. This breakdown of the problem into sub-problems reduces complexity.

The AHP specifies a decision-making process that incorporates the decision-maker's information via the burden quantification scale. The benefits of the method listed above frequently outweigh its drawbacks, demonstrating the wide spectrum of multicriteria issues where AHP has found applicability (Galliou, 2009):

- Select an alternative from a set of alternatives.
- Evaluate/prioritize some alternatives over others.
- Resource allocation – finding the best combination of alternatives under certain constraints.
- Delineation of certain processes or systems based on some other processes or systems.
- Quality management.

Table 12: Table: indicative table to be completed for the AHP criteria

Criteria Weights	Criteria 1	Criteria 2	Criteria 3
Criteria 1	1		
Criteria 2		1	
Criteria 3			1

Table 13: Table: indicative table of alternatives to the AHP, once for each criterion
Sources: Gaitanaros Dimitrios. (2017). "Applications of different Multicriteria Analysis methods for Water Resources Management: The case of the Lake Karla basin".

Altern. Weights	Scen. 2	Scen.2a	Scen.2b	Scen.2c	Scen.2d
Scen. 2	1				
Scen.2a		1			
Scen.2b			1		
Scen.2c				1	
Scen.2d					1

The AHP, in particular, attempts to reduce a multi-criteria decision-making problem to a series of smaller, self-contained analyses based on the observation that the human mind is incapable of considering too many factors simultaneously when making a decision (Miller, 1956; Saaty, 1980; Arrow and Raynaud, 1986). It starts by organizing the elements of the analysis into three main hierarchical levels, as shown in Figure 3: the overall goal of the decision-making problem at the top, a set of (ideally, mutually preferential independent) decision criteria in the middle layer, and a set of competing options at the bottom. If the criteria need to be broken down into sub-criteria, a third layer can be added.

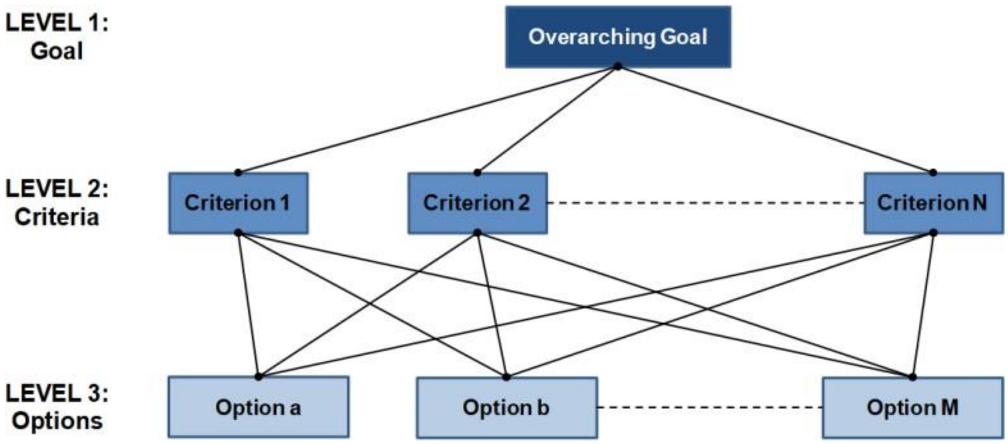


Figure 37: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Once this three-level hierarchy has been established, the AHP entails evaluating the relative importance of each criterion (second level) in relation to the analysis's purpose (first level). This is established by first doing a number of pairwise criterion comparisons. With N criteria, N(N-1)/2 pairwise comparisons are required. Subjective judgments about the relevance of the various criteria are converted into quantitative scores using a discrete, nine- to sixteen-point semantic scale ranging from 1 (when the two criteria under consideration are 'equally preferred') to 9 (when one criterion is 'preferred very strongly' over the other). The results of the pairwise comparison of several criteria are organized in a matrix, as shown in Figure 4. Following the building of the pairwise comparison matrix, the actual priority (or weight) of each criterion is obtained. The most rigorous, but also computationally costly, way is to compute the matrix's normalised principal eigenvector (Saaty, 2003).

A considerably simpler method for determining criterion weights is to compute the geometric mean of each row and then normalize the resultant new column of the pairwise comparison matrix (Saaty, 2001), as shown in the figure below. In most cases, this approximation method yields results that are sufficiently near to the eigenvector method (Rogers and Duffy, 2012; Barfod and Leleur, 2014).

Following that, the local priority of each option (third level) in relation to the decision criteria (second level) must be determined. The relative worth of each option is also determined by doing a pairwise comparison (using the same nine-point semantic scale) of the relative performance ratings for all project option combinations, independently for each choice criterion used in the analysis. There are M(M-1)/2 pairwise comparisons for each criterion when there are M alternatives. The same procedure is then used to determine the local priority (or score) of each option with reference to each criterion, which involves computing the normalised principal eigenvector (or the normalised geometric means) of the pairwise comparison matrices of the options (one matrix for each decision criterion considered in the analysis). Example of pairwise criterion comparisons using the AHP method:

'Greenhouse Gas Reduction' is more important than 'Economic Growth'

'Greenhouse Gas Reduction' is slightly more important than 'Equity'

'Greenhouse Gas Reduction' is strongly more important than 'Strategic Fit'

Criteria	Greenhouse Gas Reduction	Economic Benefits	Equity	Strategic Fit	Geometric mean*	Normalised Weights
Greenhouse Gas Reduction	1	4	3	7	3.03	3.03/5.54 = 0.55
Economic Growth	1/4	1	1/3	3	0.71	0.71/5.54 = 0.13
Equity	1/3	3	1	5	1.50	1.50/5.54 = 0.27
Strategic Fit	1/7	1/3	1/5	1	0.31	0.31/5.54 = 0.06
				Total	5.54	1

*Geometric mean = $\sqrt[n]{x_1 x_2 \cdots x_n}$

Figure 38: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Finally, once weights and scores have been determined (both score and weights are mapped onto a 0 to 1 scale), the overall valuation V of an option an in relation to the overall goal of the analysis and N decision criteria is calculated by adding the products of each criterion weight and a's performance in relation to that criterion. This is stated mathematically as (Dean, 2022):

$$V(a) = \sum_{j=1}^{N} w_j \times x_j(a) = w_1 \times x_1(a) + w_2 \times x_2(a) + \ldots + w_N \times x_N(a) \quad (2)$$

Where:
xj (a) is the local priority (performance score) of option a with reference to the j-th criterion; and wj is the priority (weight) of the j-th criterion.

3. Methods of Partial Aggregation:

A typical multi-criteria problem is represented by a situation in which there is no optimal solution: option a1 may be better than option a2 according to one criterion but worse than a2 according to another, making it impossible to identify the 'best' course of action. This condition is shown in the figure below, and it is known as the'multicriteria imbroglio' (Schärlig 1985). A multi-dimensional problem is transformed into a mono-criterion problem using full aggregation MCA methods, in which alternative solutions are appraised and ranked based on their total performance index represented on a unidimensional scale.

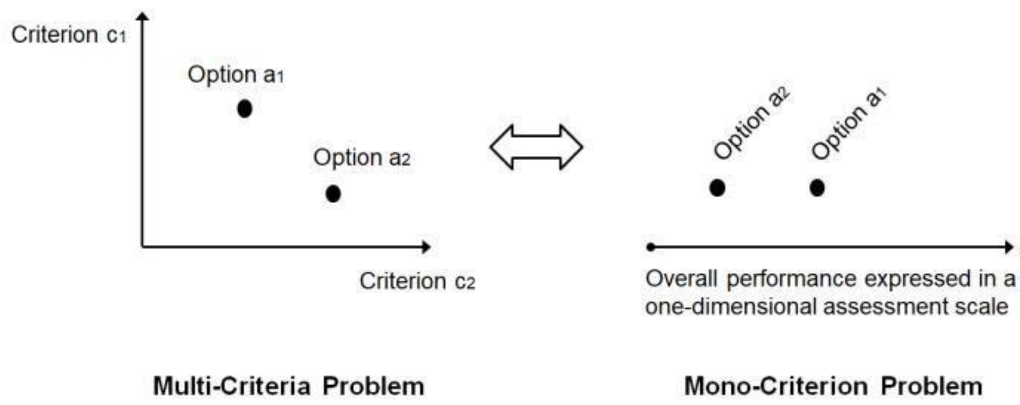


Figure 39: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Based on the concept of outranking, such algorithms compare possibilities on a pairwise basis with respect to each specific criterion. The goal is to determine the level of dominance that one option has over another. An option is said to outrank (or dominate) another if there is sufficient evidence to support the conclusion that the former outperforms the latter on enough criteria (of sufficient importance), while there is insufficient evidence to show that this statement is false with respect to the remaining criteria (Roy, 1996). As a result, with discrete, partial aggregation methods, the output of an analysis is an outranking relation on the collection of alternatives rather than an overall value for each alternative:

Figure 6 – Illustrative example of the decision model implied by partial aggregation (outranking) MCA methods. Comparison between two alternative options (a_3 and a_4).

Criteria	Weights	Performance Scores of Options			
		a_1	a_2	a_3	a_4
C_1	1/5	1	4	3	5
C_2	1/5	4	3	4	1
C_3	1/5	3	3	4	1
C_4	1/5	3	5	4	2
C_5	1/5	4	2	3	1

$X_1(a_3) = 3 < X_1(a_4) = 5$

$X_2(a_3) = 4 > X_2(a_4) = 1$

$X_3(a_3) = 4 > X_3(a_4) = 1$

$X_4(a_3) = 4 > X_4(a_4) = 2$

$X_5(a_3) = 3 > X_5(a_4) = 1$

Enough evidence to conclude that $a_3 > a_4$

Figure 40: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. Figure 6 In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

The various discrete, partial aggregation (or outranking) MCA methods differ in terms of the types of data and information they can handle (e.g., quantitative or qualitative, complete or fuzzy), as well as the rules and procedures used to determine the level of dominance of one option over the others (see, for example, Brans and Mareschal, 2005; Figueira et al., 2005c; Martel and Matarazzo, 2005). In its most basic form (i.e. PROMETHEE I), the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) attempts to calculate a Preference Index that assesses the strength of the assertion 'option a1 outranks option a2' (Brans and Vincke, 1985). The first version of the ELECTRE family methods, whose French acronym stands for ELimination Et Choix Traduisant la REalité, or Elimination and Choice Translating Reality, takes this approach a step further by calculating a Concordance Index and a Discordance Index (Roy, 1968).

The Concordance Index, like PROMETHEE I's Preference Index, measures the preference for choice a1 over option a2. The Discordance Index, as a companion to the Concordance Index, highlights evidence that may contradict the statement 'option a1 dominates option a2' and quantifies the extent to which a1 is worse than a2 on any of the criteria. To account for imprecision and uncertainty in preference elicitation, precise threshold levels are set, with which the concordance and discordance measures must comply in order for the evidence to be compelling (Roy, 1996; Rogers et al., 2000). Concordance and discordance thresholds, on the other hand, take on varied values depending on the outranking method and application. Subjectivity in indices, preference thresholds, and all other critical factors and phases of the analysis raises legitimate issues about dependability (Roy and Bouyssou, 1986; Cook et al., 1988).

Outranking MCA methods, in contrast to full aggregation MCA methods, are partially or non-compensatory because a poor score against one criterion cannot (or only partially) be compensated for by a higher score against another criterion. As a result, an option that performs well on all criteria is more likely to outperform another option that has extraordinarily high scores on several criteria but performs poorly on others. Weights now take on the (more obvious) sense of significance coefficients, which measure the influence that each criterion

should have in constructing the case for the argument that one alternative is superior to another(Munda, 2008; Bouyssou et al., 2000; Belton and Stewart, 2002).
At last, it is crucial to highlight that such procedures do not always result in a comprehensive ranking of the possibilities because the concept of 'incomparability' is permitted (that is, where there is no vital evidence to establish that one option is superior or inferior to another). Whereas incomparability between some solutions is frequently difficult for decision-making, it may also help highlight some parts of the problem that may require a more complete investigation (Rogers and Duffy, 2012).

3.1.7 Simplified Methods

Many people working on MCA applications simply do not have the time, resources, or skills to solve complex equation systems, develop utility functions, or do a large number of pairwise comparisons. Simple summary charts, simple additive weighing algorithms, checklists, and other screening tools are examples of elementary MCA procedures. Because they have less rigid restrictions than formal approaches, simplified MCA methods are often extremely flexible and easily adaptive to many types of situations. Furthermore, whereas the fundamental principles of formal MCA approaches are sometimes only fully grasped by MCA professionals, and the mathematical algorithms at their heart are frequently locked within proprietary software, simpler MCA methods can be run and understood virtually by anybody. However, it must be noted that, if used improperly (with no consideration of even the most basic rules), elementary methods are extremely likely to lead to many inconsistencies and errors (e.g. inaccurate selection of criteria leading to the violation of the preferential independence condition as well as to double-counting problems; incorrect weighting and scoring procedures; discrepancies between the weighting elicitation methods and the actual meaning of weights; methodologically unsound rules to combine scores and weights).

1. **Simple Multi-Criteria Summary Charts:** In this method, the performance of the option(s) under consideration against the many criteria used for the study is simply displayed using tables, graphs, or diagrams without the addition of scores and weights. While (quantitative or qualitative) performance scores may be provided in some situations, there is no attempt to calculate a global score or rank the project possibilities under consideration in a mechanical fashion. The emphasis of this presentational approach is clearly on 'opening up' the analysis (Stirling, 2006 and 2008), with various types of charts that provide analysts and decision-makers with a comprehensive overview of the key features and impacts of the option(s) under consideration and assist them in better understanding the problem situation.

Example of a simple summary table that displays the performances of a hypothetical road project against different criteria. Neither scores nor weights are used in the table:

Table 14: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Objectives/Criteria	Quantitative Impacts	Qualitative Impacts
Greenhouse Gases	Increase in greenhouse gas emissions as a result of the project: +120 tonnes of CO_2 over 60 year appraisal period	Not Applicable
Heritage of Historic Resources	No demolition of any historic building would be required	The proposal could be implemented with full respect of the historical character of the area.
Accident Reduction	Several car accidents potentially prevented by the construction of the road (over 60 year appraisal period): fatal = 20; serious = 125; slight = 400.	Driver stress likely to be reduced
Transprot Economic Efficiency	The project would generate large benefits for business users from travel time and vehicle operating cost savings: Present Value of Benefits = £125.8m	Not Applicable
Integration/ Strategic Fit	Not Applicable	• The project aligns with local and regional transport objectives • Conflicts with environmental and sustainability objectives at all levels.

Example of a simple MCA summary diagram showing the performances of three different options. Scores are used for illustrative purpose only and there is no attempt to rank the options in a mechanistic way:

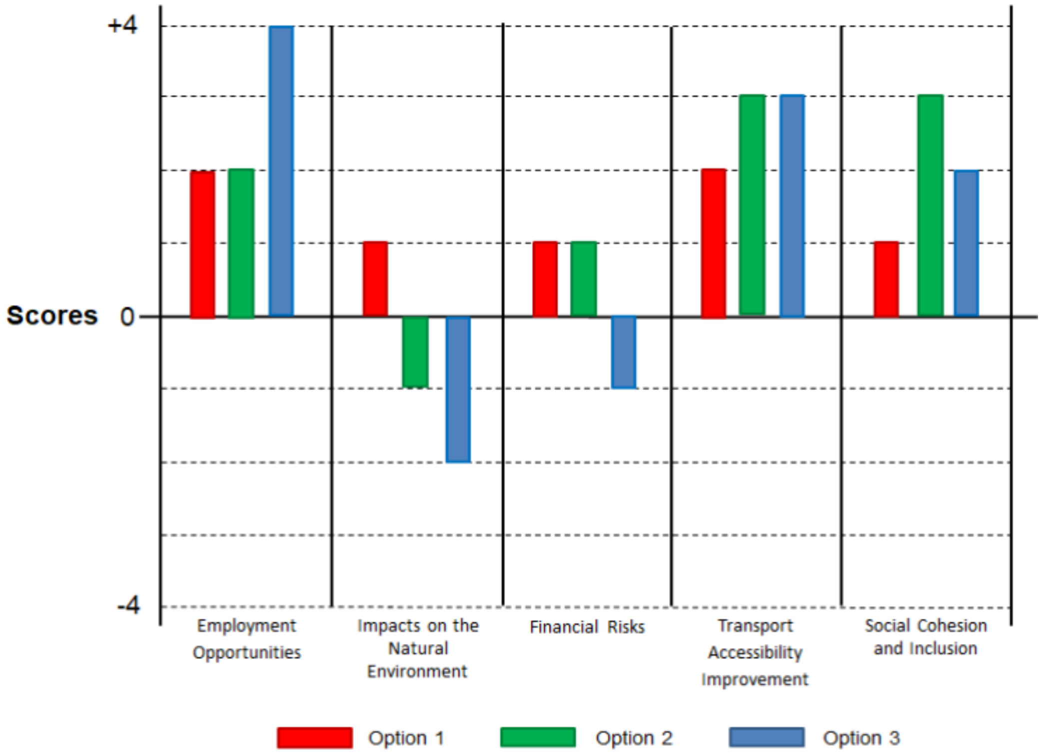


Figure 41: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

2. **Simple Additive weighing methods:** One of the most well-known and extensively used decision-support approaches based on many criteria is simple additive weighing methods. In order to calculate the overall performance of the various options under consideration, these approaches use the very simple and appealing weighted additive model (typical of some MAUT applications, AHP, SMART, and numerous other complete aggregation MCA methods). Thus, the emphasis here is on 'closing down' the analysis (Stirling, 2006 and 2008) with global scores, obtained as the weighted sum of the individual performance scores, that clearly indicate to analysts and decisionmakers what the 'optimal' alternative to address the problem at hand is. The process results are typically displayed as performance tables, where each row identifies a specific criterion and the columns provide the respective weights and performance scores of the option(s) under consideration against that criterion. While these methods are simple and straightforward, they lack the theoretical rigor of formal methods and frequently resemble rudimental weighted average computations with few, if any, ties to MCA theory.

Example of a performance table presenting the result of a MCA based on a simple additive weighting model:

Table 15: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Objectives/ Criteria	Weights (0÷100%)	Option 1		Option 2		Option 3	
		Scores (0÷10)	Weighted Scores	Scores (0÷10)	Weighted Scores	Scores (0÷10)	Weighted Scores
Strategic Fit	25%	4	1	8	2	10	2.5
Wider Ec. Benefits	10%	4	0.4	6	0.6	5	0.5
Env. Impacts	15%	2	0.3	7	1.05	4	0.6
Equity	30%	5	1.5	7	2.1	8	2.4
Implement. Risks	20%	9	1.8	2	0.4	8	1.6
Total	**100%**		**5**		**6.15**		**7.6**
Preference Rank		**3**		**2**		**1**	

3. **Multi-Criteria Checklists and Other Screening Tools:** This category includes several basic and intuitive types of MCA that do not require numerical techniques and are frequently used (instinctively) by many people in their daily decisions. Basic checklists and lexicographic orderings are two common examples of such methods. They can be useful at the start of the planning and decision-making process to screen out some options and find the most feasible options, which will then be developed and examined further. The different objectives and criteria are ordered into different priority levels with basic lexicographic orderings, and the various options are ranked or screened in/out against one criterion at a time, beginning with the most important and ending with the least important. If an alternative clearly appears to be the best in terms of the first criterion, the procedure is completed and that option is chosen as the preferred one. If more than one option outperforms the most important criterion, the subset of possibilities is then compared against the second most important criterion. The process is repeated in this manner until a single alternative is picked 23 or until all of the criteria have been met and total separation between possibilities is proven to be unachievable.

Example of a multi-criteria checklist:

Objective/ Criteria	Options			
	a1	a2	a3	a4
Strategic Fit	V	X	V	V
Social Acceptability	V	V	V	X
Affordability	V	V	V	V
Implementation Risks	X	V	V	X

Figure 42: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Example of a lexicographic ordering:

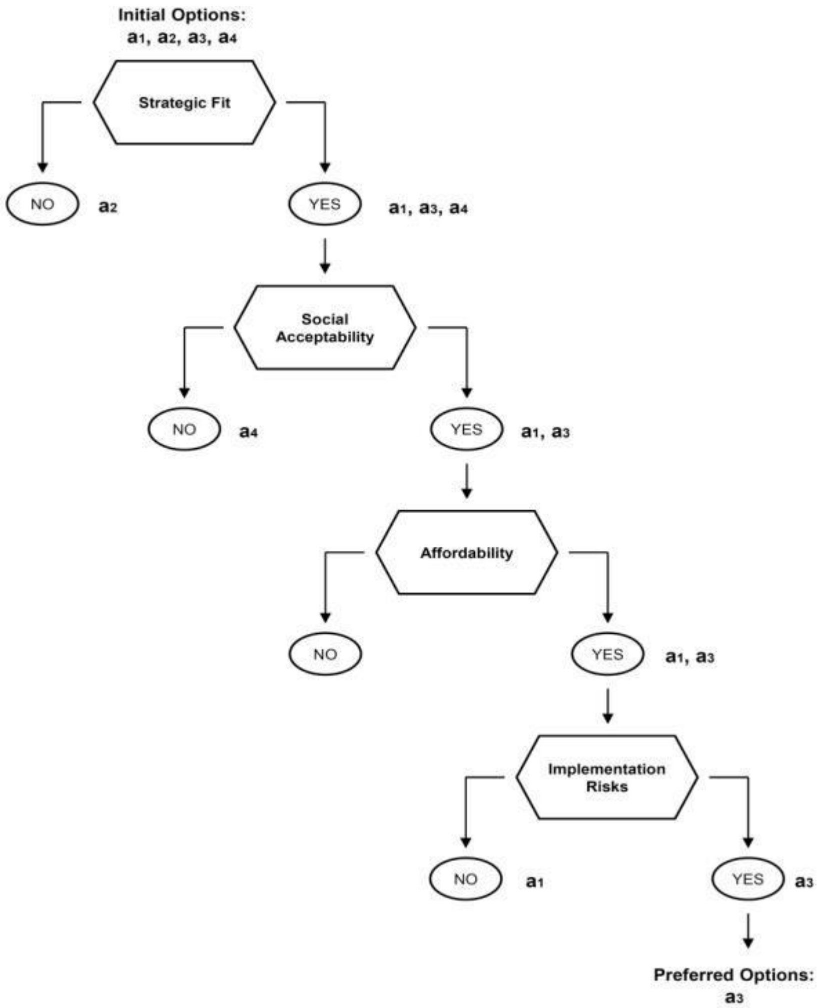


Figure 43: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

3.1.8 Non-Participatory and Participatory Approaches to Multi-Criteria Analysis

Monitoring and assessment can be done either non-participatory (analyst-led) or participatory. The analysis is carried out independently by one analyst or a team of researchers and professional advisors in non-participatory assessments, following a standard technocratic approach. The analysts collect, process, and interpret data and information (using various decision-support methods and tools), taking (to the greatest extent possible) a general and independent view of the problem at hand, and eventually presenting the results of the analysis to one or a few decision-makers (e.g., a Minister or a Government Department; a person, a group of individuals, or a committee with decision-making authority).

One significant argument in favor of this strategy is that a group of highly qualified professionals is best equipped to supporting complex and critical choices. Participatory procedures, on the other hand, use a more collaborative and (in theory) more democratic decision-making style, with the direct involvement of various interested and impacted persons (i.e. problem stakeholders) in the analysis. As a result, analysts and decisionmakers may be able to account for overlooked views, excluded possibilities, and overlooked difficulties to the greatest extent possible. The best technique depends on the nature of the problem at hand as well as the resources available to carry out the study. An analyst-led strategy with no stakeholder participation may be better appropriate for tackling purely technical problems with minimal degrees of uncertainty and ambiguity. More complex and uncertain policy issues affecting society as a whole, on the other hand, may be better addressed through (longer and more expensive) participatory processes in order to ensure that all the different perspectives on the decision situation are adequately represented (Funtowicz and Ravetz, 1991; Stirling, 1998 and 2006; Renn 2015).

Participatory MCA approaches thus include certain group decision-making participants in addition to analysts and decision-makers. The latter often consists of problem stakeholders and, in some cases, academics and specialists in an attempt to incorporate a more scientific perspective in the investigation. Participants may participate in the multi-actor multi-criteria exercise either individually or as representatives of organized groups (for example, local community groups, landowners, business groups, environmental specialists). In terms of operation, the phases of participatory MCA techniques are similar to those of analystled MCA and typically include the following stages (which can occur in different orders and manners): Option development; creation of objectives and criteria against which to test choices; scoring of options' impacts against the various criteria: as well as criteria weighting.

However, unlike analyst-led procedures, group decisionmaking participants in participatory MCA techniques can contribute to the identification of the important aspects of the multi-criteria framework (i.e. alternatives, objectives and criteria, weights and scores). MCA methodological modifications to group decision-making appear to have occurred principally in three primary categories (Dean, 2018):

- Identification, classification, and selection of group decision-making participants;
- Involvement of stakeholders (and experts) in group process analysis and management; and
- Collection, processing, and inclusion of preferences of group decision-making participants in the multi-criteria framework.

Each domain, however, entails some critical dilemmas and methodological challenges.

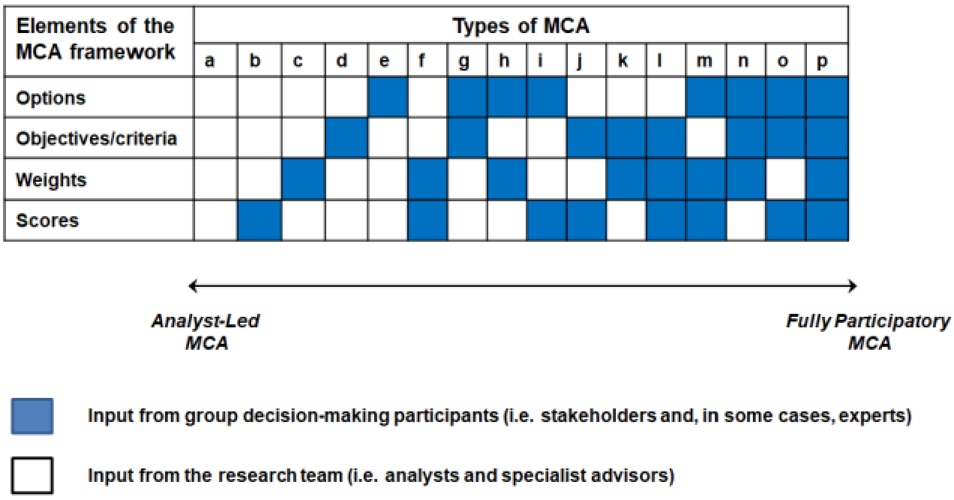


Figure 44: Types of participatory MCA methods – Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Furthermore, it is obvious that, while potentially useful for ensuring a thorough assessment of the problem, including stakeholder groups and other interested parties in the analysis exponentially increases the complexity of the MCA exercise. Indeed, an analyst-led strategy would solve a typical discrete multi-criteria decision-making problem with a finite set A of M alternatives, A = {a1, a2, a3,... aM}, and a set C of N criteria, C = {c1, c2, c3,... cN}, characterized by and a set of weights W = {w1, w2, w3, ..., wN}, can be synthetically represented by a N×M matrix, whose typical element xj(ai) (i = 1, 2, ..., M; j = 1, 2, ..., N) represents the evaluation of the i-th alternative by means of the j-th criterion.

Example: Tabular representation of a multi-criteria decision-making problem under an analystled approach to MCA

Criteria	Weights	Options				
		a_1	a_2	a_3		a_M
c_1	w_1	$x_1(a_1)$	$x_1(a_2)$	$x_1(a_3)$		$x_1(a_M)$
c_2	w_2	$x_2(a_1)$	$x_2(a_2)$	$x_2(a_3)$		$x_2(a_M)$
c_3	w_3	$x_3(a_1)$	$x_3(a_2)$	$x_3(a_3)$		$x_3(a_M)$
c_N	w_N	$x_N(a_1)$	$x_N(a_2)$	$x_N(a_3)$		$x_N(a_M)$

Figure 45: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

In contrast, the problem in a multi-actor multi-criteria exercise involving G group decision-making participants is defined by a three-dimensional matrix NMG, which includes the preferences of the many parties involved in the exercise. When participants are given the option of scoring the consequences of the options under consideration, the generic element of the matrix xj(ai) K (i = 1, 2,..., M; j = 1, 2,..., N; k = 1, 2, 3,..., G) represents the evaluation of the i-th alternative using the j-th criterion from the perspective of the k-th group decisionmaking participant.

Besides, if participants are also given the opportunity to identify their own list of objectives and criteria, as well as the weights of these criteria (Approach 'L' in Figure 9), the set C of criteria and the set W of weights can vary depending on the person (or group) conducting the assessment. In general, because different stakeholder groups have different interests and objectives, a participatory MCA process may result in as many lists of criteria, weighting schemes, and sets of scores as the number of groups involved. When a multi-actor multi-criteria exercise involves a large number of participants (as a participatory process on a large-scale transportation project or another major policy problem would theoretically necessitate), the multi-criteria framework can quickly become difficult (if not impossible) to manage and evaluate.

Example: Tabular representation of a multi-criteria decision-making problem under a participatory approach to MCA

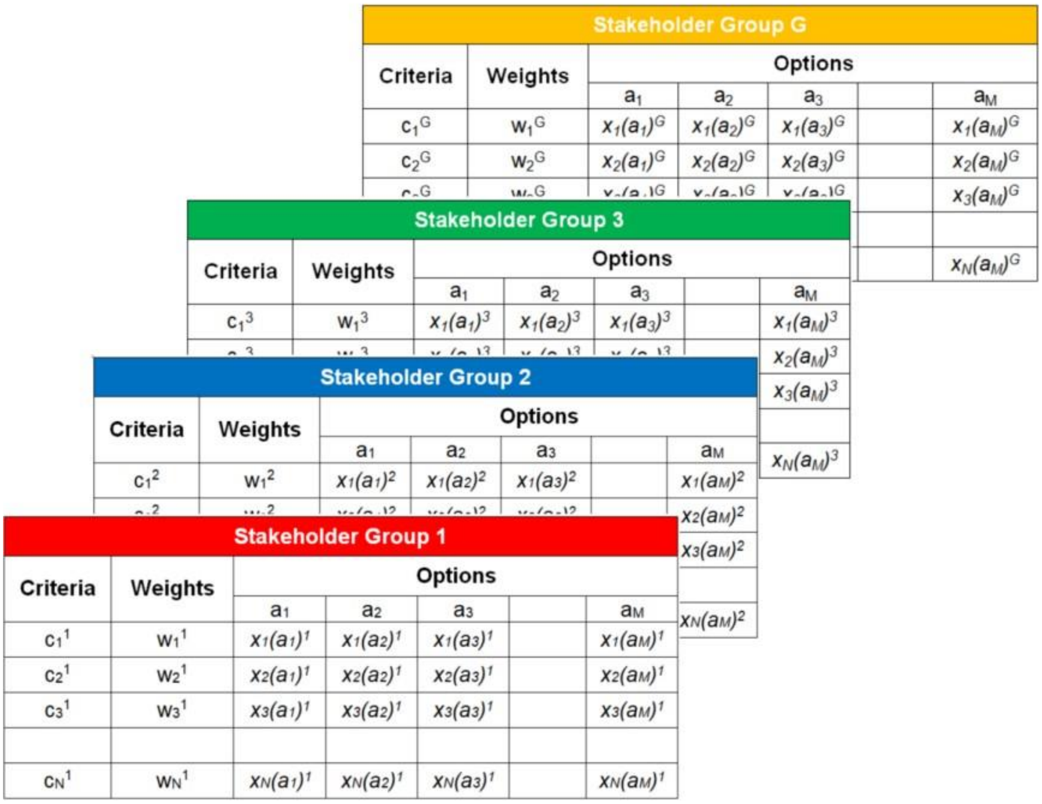


Figure 46: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Ultimately, one of the most important aspects of participatory MCA is how the interests and priorities of the various stakeholder groups are collected and processed to determine the options, the list of objectives and appraisal criteria, the set of scores, and/or the weighting scheme. Different techniques are feasible, as shown in the Figure (Dean, 2018, 2021 and 2022; Dean et al., 2019). The points of view of the process's actors and groups can be kept separate from one another in order to highlight better differences and similarities in the perspectives of each of the group decision-making participants.

However, as previously stated, the resulting multi-criteria framework is very likely to become too complex (i.e. a number of diverse and conflicting lists of criteria, weighting systems, and sets of scores) to be employed directly in decision assisting. Alternatively, the participants' points of view can be aggregated together by calculating the mathematical average of a range of values or creating a representative value that minimizes the variances between participants' points of view. Although easy, this technique is methodologically poor and addresses stakeholder issues only temporarily. Finally, in theory, a shared multicriteria framework can be obtained by talks and negotiations among 28 parties. However, such a negotiating process is exceedingly difficult to manage and carries a significant risk of deadlock, especially when stakeholders have diametrically opposed interests with little space for compromise.

Example: Possible strategies for including multiple perspectives in participatory MCA

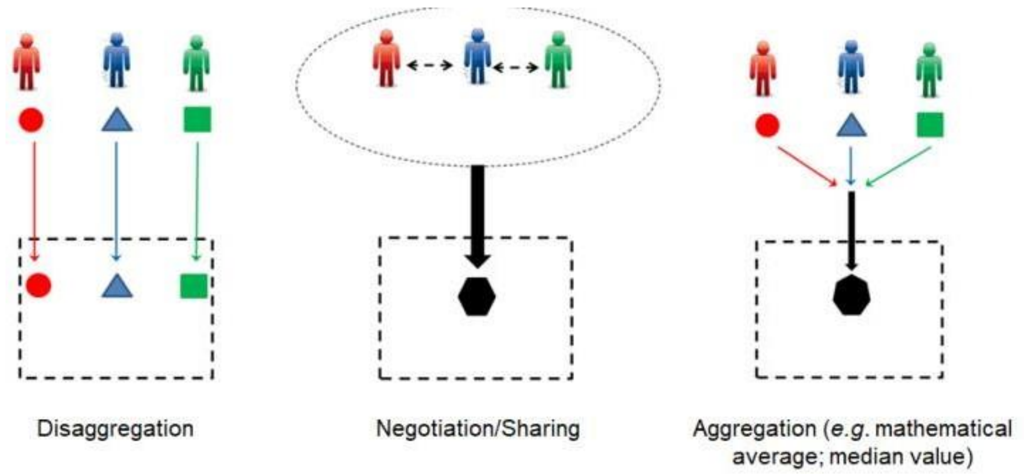


Figure 47: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Many additional features and issues must also be carefully evaluated before embarking on a multi-actor multi-criteria appraisal exercise. However, a complete examination of participatory MCA is beyond the scope of this work. The sections that follow depict the essential steps of a basic, analyst-led MCA exercise, while Dean (2018, 2021, and 2022) and Dean and colleagues (2019) provide a more extensive assessment of participatory MCA approaches.

3.1.9 Other MCA Methods

The Multi-attribute utility theory as described in the Department of Communities and Government publication "Multi-criteria analysis: a manual" (2009) states: There is no critic-free normative model of how individuals should make multi-criteria choices. The one that is most widely accepted is based on multi-attribute utility theory and draws from the 1940s and 1950s work of von Neumann and Morgenstern, as well as Savage. While this research provides valuable theoretical insights, it does not immediately assist decision makers in undertaking difficult multi-criteria choice tasks.

The work of Keeney and Raiffa, published in 1976, was a watershed moment in this regard. They created a set of methods that would allow decision makers to analyze multi-criteria options in practice while adhering to the preceding normative grounds. The Keeney and Raiffa approach is potentially difficult to use because it takes uncertainty officially into account, incorporating it directly into decision support models, and secondly, it allows qualities to interact with each other in ways other than a straightforward, additive pattern. It does not presume that preferences are mutually independent. In some cases, it may be necessary to incorporate one or both of these factors into the analysis, but in practice, it may be preferable to ignore them in order to allow for a simpler and more transparent decision support to be implemented more quickly, by a broader range of users, and for a broader set of problem types (Dept. Communties & Goverment , 2009).

3.1.10 Linear additive models

If the criteria can be proven or reasonably considered to be preferred independent of each other, and if uncertainty is not officially included into the MCA model, the simple linear additive evaluation model is suitable. The linear model demonstrates how the values of an option on the many criteria can be blended into a single overall value. This is accomplished by increasing the value score on each criterion by its weight, and then combining all of the weighted values together. This easy arithmetic, however, is only applicable if the criteria are mutually choice independent. This type of model has a proven track record of providing strong and effective support to decision-makers working on a variety of problems and under a variety of conditions. They will serve as the foundation for future thorough work (Dept. of Communities and Government, 2009).

3.1.11 Outranking methods

A rather different method than those outlined thus far was devised in France and has gained some traction in some continental European countries. It is determined by the concept of outranking. Outranking is used in all of the strategies that have evolved to try to eliminate alternatives that are 'dominated' in some way. In contrast to the basic dominance concept, dominance inside the outranking frame of reference employs weights to give more weight to some criteria than others.

One option is said to outrank another if it outperforms the other on enough criteria of sufficient importance (as expressed by the sum of the criteria weights) while not being considerably outscored by the other option on any one criterion. All options are then evaluated in terms of the amount to which they outrank the entire set of options being considered, as measured against a pair of threshold parameters.

One intriguing aspect of outranking approaches is that, under certain conditions, two options might be categorized as 'incomparable' ('difficult to compare' is probably a better way to convey the idea). Incomparability of two options is not the same as indifference between two options and may be connected with insufficient knowledge at the time of assessment. This is a common occurrence in many decision-making processes.

Building this possibility into the mathematical framework of outranking permits formal examination of the problem to continue without imposing an unsupportable judgement of indifference or abandoning the option entirely because information is unavailable. The main criticism leveled at the outranking strategy is that it is based on arbitrary definitions of what really constitutes outranking and how the threshold parameters are set and then modified by the decision maker. However, the concept of outranking captures some of the political realities of decision making in a roundabout way. It degrades choices that do poorly on any one criterion in particular (which may result in considerable lobbying from relevant parties and difficulty in implementing the option in question). It can also be a useful tool for investigating how preferences between options are established.

3.1.12 Procedures that use qualitative data inputs

The paper’s viewpoint is that numerical weights and cardinal scale scores provide the most dependable and transparent decision-making guidance. There are several exceptions, such as the usage of dominance and models that mimic the linear additive model but are based on weight ranking (Appendix 4). However, it is a fair assumption that the less exact the data inputs to any decision support technique, the less precise and dependable the outputs generated.

Nonetheless, government decision-makers are regularly confronted with situations in which the information in the performance matrix or concerning preference weights consists of qualitative judgments. There are several ways to reply to this (Dept. of Communities and Government, 2009).

3.1.13 MCA methods based on fuzzy sets

In response to the imprecision that surrounds most of the data on which public decision making is based, one approach has been to look to the rapidly forming topic of fuzzy sets to provide a foundation for decision making models. However, such methods are not yet commonly used. Fuzzy sets aim to convey the idea that our natural language is not precise when addressing difficulties. Options are 'pretty attractive' or 'quite pricey' from a specific point of view, not merely 'attractive' or 'expensive'. Fuzzy arithmetic then attempts to capture these qualified judgments through the concept of a membership function, in which an option would belong to the set of, say, 'attractive' alternatives with a particular degree of membership, ranging from 0 to 1.

Fuzzy MCA models establish processes for aggregating fuzzy performance levels utilizing weights that are sometimes also represented as fuzzy quantities based on assessments provided in this manner. However, these methods are difficult for nonspecialists to understand, lack clear theoretical foundations in terms of modeling decision makers' preferences, and have yet to demonstrate any critical advantages that are not available in other, more conventional models. They are unlikely to be useful in government for the foreseeable future.

The preceding sections have provided an overview of some of the major types of MCA models that have been proposed as possibly applicable to public sector decision making. There are numerous others, some of which having a track record of application, but many of which have not progressed much beyond the conceptual stage. Methods based on Rough Sets or Ideal Points, as well as several methods heavily reliant on interactive development using specially constructed computer packages, are examples of categories that have not been explicitly discussed but are mentioned in the MCA literature. None of these are likely to find extensive use in mainstream public sector decision making for a variety of reasons.

3.1.14 Objectives Identification

The key goals against which the proposed solutions are finally analyzed and contrasted are represented by objectives. The quantity and type of objectives to include in the multi-criteria framework are mostly determined by the decision-making circumstances at hand. In general, early analyses require only a few essential aspects to be considered, whereas detailed and in-depth assessments necessitate a more comprehensive list of objectives and hence require more data. The team of analysts and professional advisers doing the analysis might draw on numerous sources to generate a list of objectives, including:

- Key planning and policy papers pertaining to the topic at hand
- Broad guidelines, checklists, and generic multi-criteria frameworks created by government departments, agencies, or academics.
- Previous appraisal and assessment reports on similar decision-making scenarios.
- Information acquired from documents, reports, interviews, and surveys about the interests and priorities of decision-makers and other problem stakeholders.

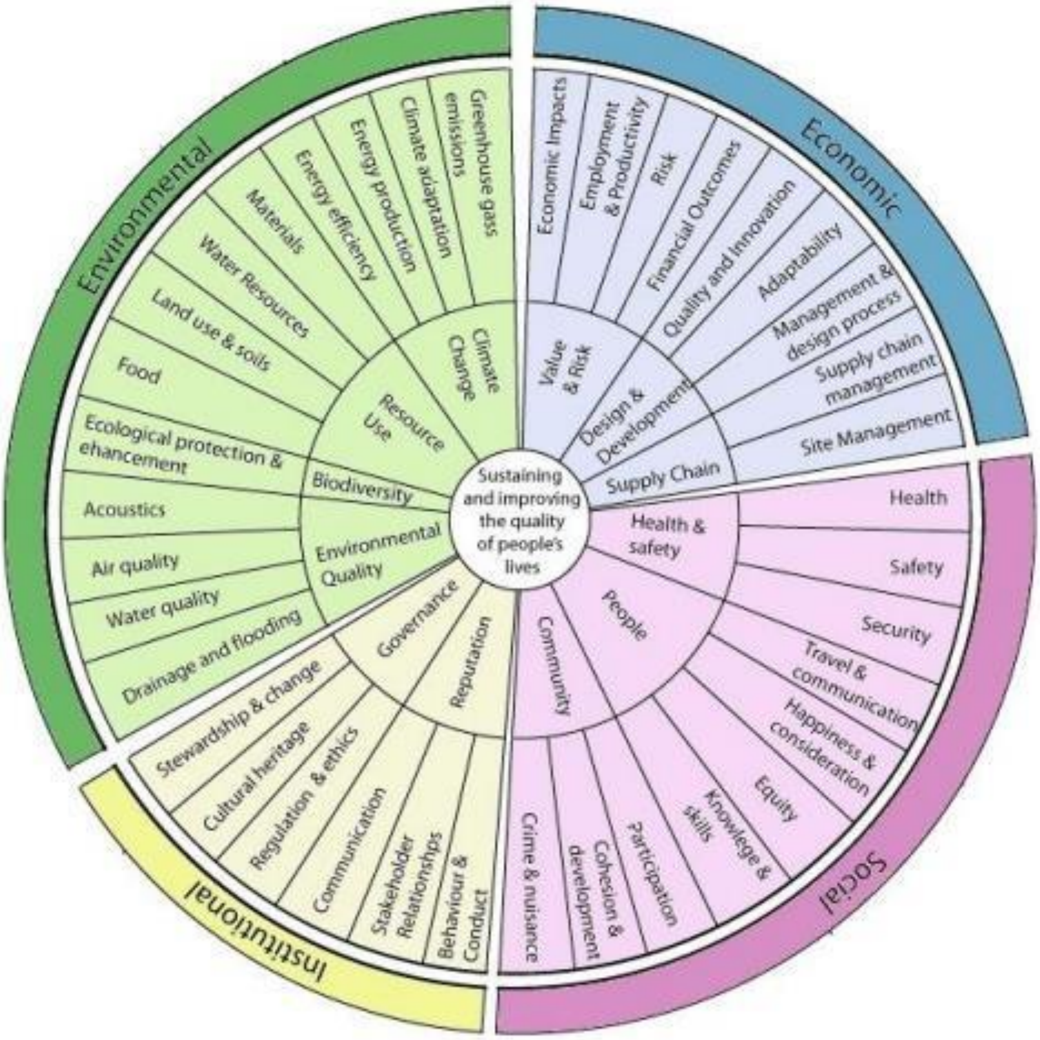


Figure 48: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722 - Citing Dimitriou et. al (2010)

3.1.15 The stages of a multi-criteria analysis

This section provides an overview of how this performance matrix is developed and how it fits into the overall scope of a multi-criteria analysis. A complete implementation of multi-criteria analysis typically entails eight steps.

Steps 1–4 and 7 are discussed for cases in which there is no explicit numerical trade-off between requirements, i.e. where steps 5 and 6 are skipped. Multi-criteria analysis is presented as a straightforward, step-by-step procedure. However, unless the user has used the method to solve very similar problems in the past, it is better to think of it as a guided exploration of a problem. Some of the procedures will necessitate careful consideration of concerns surrounding the decision. It may be required to go back and re-visit and revise prior steps. The thinking that goes into the first steps contributes significantly to the value.

1. Establish the decision context. What are the aims of the MCA, and who are the decision makers and other key players?
2. Identify the options.
3. Identify the objectives and criteria that reflect the value associated with the consequences of each option.
4. Describe the expected performance of each option against the criteria. (If the analysis is to include steps 5 and 6, also 'score' the options, i.e. assess the value associated with the consequences of each option.)
5. 'Weighting'. Assign weights for each of the criteria to reflect their relative importance to the decision.
6. Combine the weights and scores for each of the options to derive and overall value.
7. Examine the results.
8. Conduct a sensitivity analysis of the results to changes in scores or weights.

Figure 49: Source: Dept. Communties & Goverment. (2009). Multi-criteria analysis: a manual. www.communities.gov.ukcommunity,opportunity,prosperity

According to Dr. Deans Guide the Key Steps of an Analyst – Led Multi Criteria Analysis are:

1) Primary problem analysis
2) Development of the options to be assessed
3) Identification of objectives and associated criteria against which to test options
4) Construction of the performance profile of each option
5) Scoring of impacts of each option
6) Weighting of criteria
7) Combination of scores and weights
8) Sensitivity analysis
9) Presentation of the results of the MCA exercise as a support for the final decision-making

Figure 50: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

The steps may differ (little or dramatically) depending on the type of MCA used. More formal MCA approaches often necessitate additional steps and sub-processes. The process is substantially shorter when using extremely simple methods such as simple MCA summary tables and multi-criteria checklists.

It is worth emphasizing that the use of MCA is not limited to scenarios in which the goal is to determine the single best choice to pursue. Using only the steps of the MCA process covered in this chapter can be especially useful when the goal is to short-list a set of options for further, more detailed investigation, or to group options into categories ('urgent,' 'less urgent,' 'low priority,' for example).

Key Steps of the MCA process	Multi-Criteria Summary Charts	Simple Additive Weighting Methods	Multi-Criteria Checklists	Simple Lexicographic Orderings
1) Problem analysis	V	V	V	V
2) Options	V	V	V	V
3) Objectives/Criteria	V	V	V	V
4) Performance Profile	V	V	V	V
5) Scores	Scores can be employed	V	X	X
6) Weights	X	V	X	V
7) Combinations of Scores and Weights	X	V	X	X
8) Sensitivity analysis	X	V	X	Different ordinal rankings of criteria might be tested
9) Presentation of the results	V	V	V	V

V required X not required

Figure 51: Example: MCA methods and steps of the process – Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Furthermore, as shown in the Figure below, while the first and last three steps of the procedure remain constant, the order of the other steps might vary depending on the nature of the problem under consideration. For example, while options are frequently defined early in the process (or even before its formal start), in some cases, the identification of a list of objectives and decision criteria may occur prior to the development of the possible alternative courses of action to be assessed. Weighting methods, in turn, can be carried out at the beginning of the process, immediately following the development of objectives and appraisal criteria, or at the end, following the construction of the performance profile of the alternatives and the ascription of scores. It should be emphasized, however, that numerous iterations and feedback loops between the various parts of the process are conceivable in an MCA exercise.

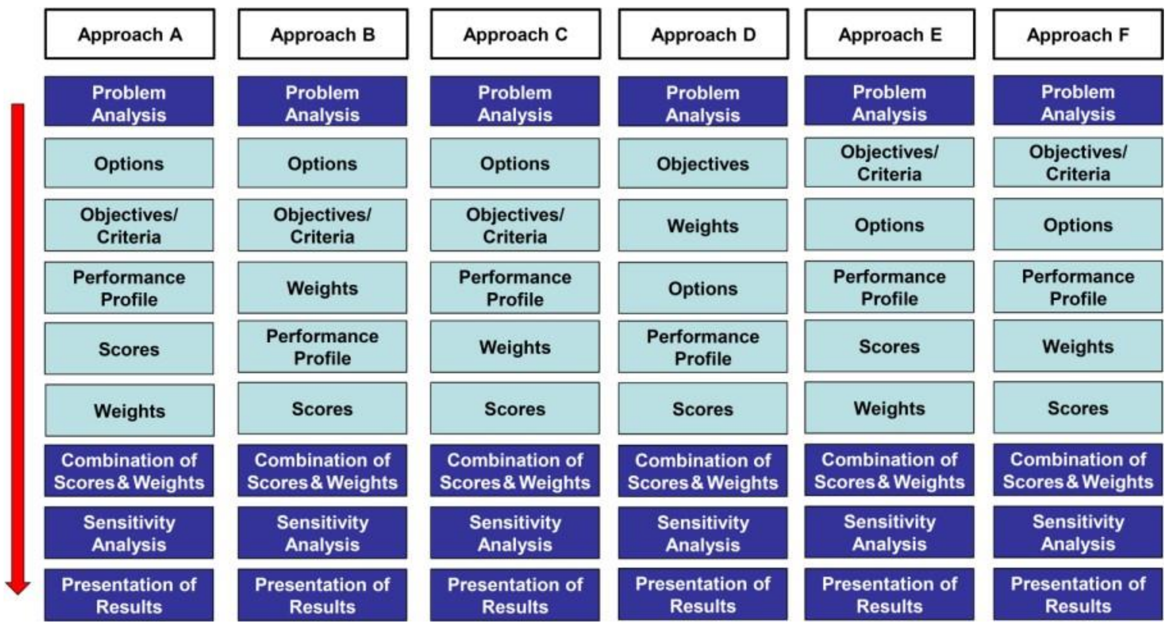


Figure 52: Example: Possible sequences of steps in a MCA process – Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Step 1: Establishing the Decision Context

A shared understanding of the decision context is always the first step. The decision context encompasses the entire set of administrative, political, and social structures that surround the issue at hand. The objectives of the decision-making body, the administrative and historical backdrop, the group of persons who may be affected by the decision, and the identification of those responsible for the decision are all key to it. It is critical to have a clear grasp of goals. What ultimate goal is this decision attempting to contribute to? MCA is all about balancing numerous competing goals. Ultimately, trade-offs must be made. Nonetheless, while using MCA, it is critical to specify a single high-level aim, for which sub-objectives are frequently defined. To define objectives (and criteria), we must first identify both the decision-makers (in order to establish objectives) and those who may be impacted by the choice. Referring to underlying policy declarations is a regular component of this stage.

Step 2: Identifying Options

Following the establishment of the decision context, the following stage is to identify the options to be examined. Even given a fresh and unanticipated situation, it is rare that the decision-making group will reach the stage of formal MCA structuring without some intuition about choices. In practice, concepts that have been 'on the books' for many years are frequently found. Sometimes the problem is an embarrassment of choices, and the MCA's duty will be to give an organized sifting of alternatives to create a shortlist, using simple data and quick procedures. It is occasionally helpful to perform some informal screening against known legal and similar constraints. It is not worthwhile to explore and expend effort obtaining data on clearly infeasible propositions. The first visit to step 2 may not be the last, especially in cases when there are few acceptable choices.

The MCA's later phases may indicate that none of the alternatives are acceptable and can aid to crystallize thoughts about where the deficiencies lie. At this point, new ideas and innovative thinking are required. The MCA will be notified of this. It may, for example, stimulate the search for new options that combine the strengths of one existing option in certain areas with the strengths of another in another. Keeney proposed that starting with alternatives is placing the cart before the horse because of the failure to be precise about objectives and to evaluate options without contemplating what is to be achieved. Options are essential only in terms of the value they add by fulfilling goals. It may be preferable to examine objectives initially, especially when options are not provided and must be developed.

Step 3: Identifying Criteria and Sub-Criteria

GENERAL APPROACH: The criteria and sub-criteria are the performance measures against which the options will be evaluated. The establishment of a solidly founded set of criteria against which to judge the possibilities accounts for a major percentage of the 'value-added' by a formal MCA process. Because the criteria serve as the MCA's performance measures, they must be operational. A measurement or a judgment must specify how well each choice satisfies the criteria's objectives. We'll come back to this later, but one thing to consider while constructing the set of criteria is "Is it doable in practice to assess or evaluate how well an option performs on these criteria?"

Specific performance indicators (one for each target) must be devised to measure the extent to which choices achieve the selected objectives. Problem structuring methods and visual aids such as value trees, which display general and broad goals, operational objectives, and specific measurable indicators of performance hierarchically, can be very useful for analysts and decision-makers to brainstorm and articulate criteria, as well as communicate the results of the analysis to the appropriate parties (Keeney and Raiffa, 1976; Chankong and Haimes, 1983; Keeney, 1992).

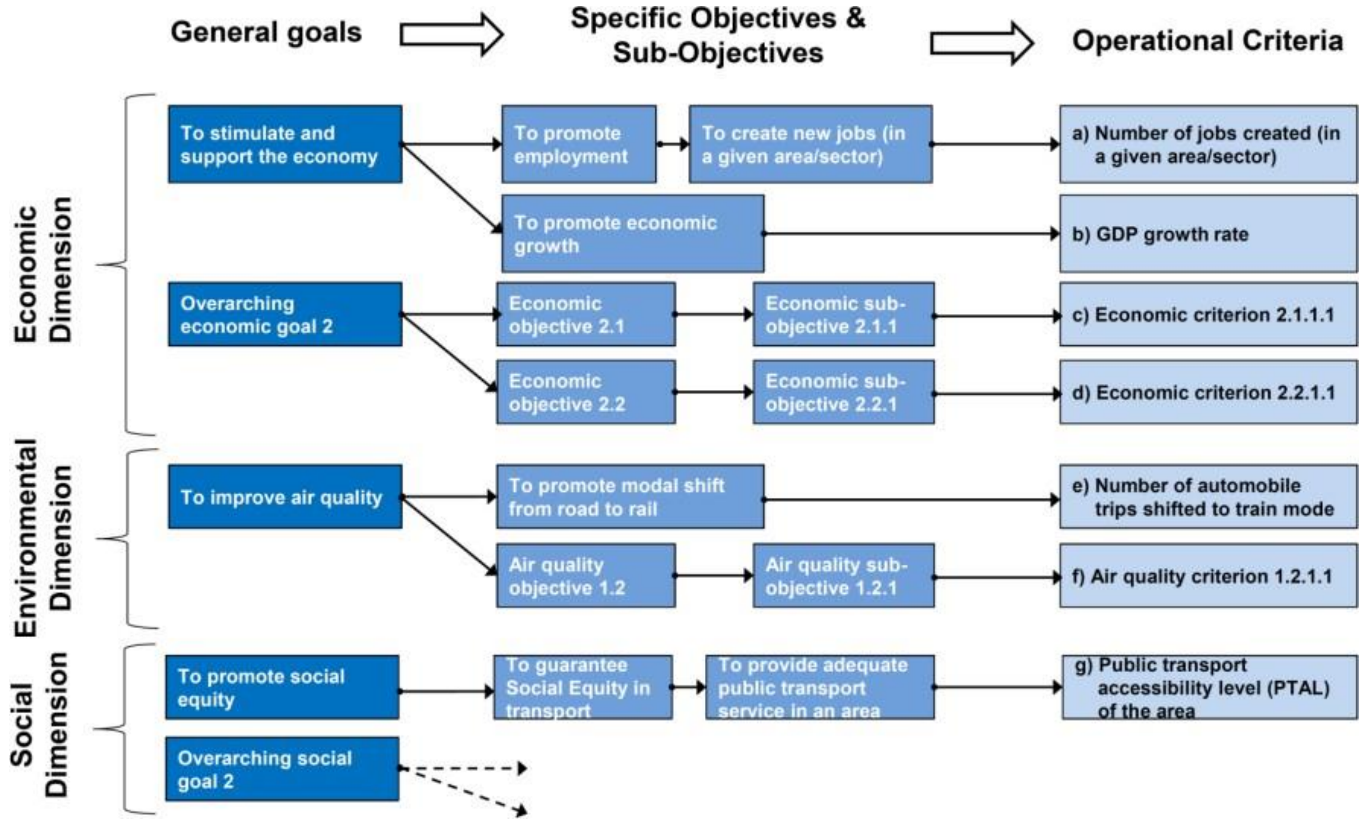


Figure 53: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Whereas most value trees of objectives and criteria are developed top-down (from fundamental values and generic goals to specific criteria), a bottom-up technique can also be used (Buede, 1986; Von Winterfeldt and Edwards, 1986). This latter approach develops criteria based on the relevant anticipated implications of the solutions under consideration, which are then grouped into broader categories (i.e. objectives and goals). The top-down method is more objective-driven, whereas the bottom-up approach places more attention on the alternatives under consideration. It is sometimes argued that there is no single correct technique to design the value tree, and that combining both approaches will result in a more comprehensive set of objectives and criteria (e.g., McAllister, 1988; Belton and Stewart, 2002; De Brucker et al., 2004; Schutte, 2010).

PROCEDURES TO DERIVE CRITERIA: An effective way to begin the process of identifying criteria, whether in a decision-making team or as an individual, is to first briefly restate step 1 and then brainstorm replies to the question "What would distinguish between a good choice and a bad choice in this decision problem?" Responses should be jotted down uncritically, possibly on whiteboards if in a communal setting. The viewpoint(s) of an interest group may be significant. One method is to directly involve the impacted parties in some or all stages of the MCA. This could be useful in some local planning difficulties, for example. A second strategy is to analyze policy statements and secondary information sources from various interest groups in order to derive criteria that reflect their concerns. A third option, provided appropriate experience exists within the decision-making team, is to urge one or more of its members to roleplay the position of major interest groups in order to ensure that this perspective is not missed when criteria are developed. Both decision-maker aims and interest group opinions are frequently expressed in broad strokes. A criterion such as environmental effect, for example, could be proposed. In many cases, evaluating solutions against such a broad criterion may be challenging, even if the concept of environmental impact is relevant. Vague criteria, like vague criteria in CBA, are often ineffective in MCA.

After an initial hesitancy, recommendations typically come thick and fast in the process of eliciting criteria, until the process finally pauses and dries up. It is typical to have a long list of prospective criteria at the end of a relatively short period. The number of criteria should be kept as short as possible while still making a sound judgment. There is no 'rule' to govern this decision, and it will undoubtedly differ from application to application. Large, financially or otherwise significant decisions with sophisticated technological characteristics (such as deciding where to place a nuclear waste facility) may include hundreds of criteria. However, a range of six to twenty is more common.

GROUPING CRITERIA: It can be useful to arrange criteria into a series of sets that pertain to distinct and distinct components of the overall decision aim. This is especially useful if the emergent decision structure has a significant number of criteria (eight or more).

The major reasons for grouping criteria are as follows:

• To aid in the process of determining if the set of criteria chosen is appropriate to the problem.

• To simplify the process of computing criteria weights in big MCDA applications, where it can be useful to analyze weights first inside groups of related criteria, and subsequently between groups of criteria.

• To promote the emergence of higher-level perspectives on the issues, notably how the options realize trade-offs between essential objectives. For both of these reasons, grouping criteria is an essential component of an MCA.

However, there are few established rules for determining what constitutes a 'good' structure and what constitutes a 'poor' one. Most experienced decision analysts regard problem structuring as a skill that is mostly learned via practice. There is arguably no unambiguously correct structure or grouping of criteria for most major problems.

An appropriate structure is simply one that represents a clear, rational, and common point of view on how to group the numerous criteria that may be relevant to an MCA evaluation into cohesive groupings, each of which tackles a single component of the overall problem. For example, when evaluating different types of medical intervention for a certain ailment, one set of criteria may be related to the patient's experience (the speed with which care may be obtained, the duration of stay in the hospital, the degree of suffering, the success of the therapy, and so on). Criteria in an MCA frequently indicate specific quantitative indications of performance relating to the issue at hand, whereas groupings of criteria reflect sub-objectives to the one main objective that underpins the MCA process.

While understanding of the domain of the specific problem can frequently provide very obvious direction as to what are clear and helpful groups of criteria, there is always room for argument. Should, for example, criteria relating to the time to the conclusion of treatment (speed of admission, length of stay) be combined into one subobjective, with criteria relating to the therapy itself placed in their own cluster? To some extent, such disagreement is beneficial and expected. It is one method by which decision makers investigate the problem to be solved and reach a shared knowledge of its characteristics and the considerations that should guide their decision.

ASSESSMENT OF THE PROVISIONAL SET OF CRITERIA

Before finalizing the criteria, the preliminary set must be evaluated against a variety of qualities.

Completeness: Have all relevant criteria been considered? This requires some caution because the relevant criteria are not always clear from the start. If a value tree has been sketched out, it can be a useful aid in this process. First, the team should go over the list of major subheadings from the criteria groups and ask themselves, "Have we missed any major category of performance?" Second, within each head, it can ask, "In this area of concern, have we included all of the criteria necessary to compare the performance of the options?" Third, do the criteria cover all of the important parts of the MCA's objectives?

Redundancy: Are there any criteria that are superfluous? In theory, criteria that were deemed relatively minor or duplicates should have been removed at an early stage, but it is always a good idea to double-check. The MCA team may also decide to remove a criterion if it appears that all of the available solutions will achieve the same level of performance when measured against it. If this were the case, leaving it out would have no effect on the ranking of possibilities and would save on analysis time. Omission on these grounds, however, should be treated with caution. Initially it has not yet been properly determined how well each option will perform on the relevant criterion. Second, it is possible that additional options will emerge later on that do not display this behavior, particularly in MCA systems that may be utilized by delegated groups and/or to handle a variety of problems.

Operationality: It is critical that each choice be evaluated against each criterion. The assessment could be objective in terms of a commonly acknowledged and understood scale of measurement, such as weight or distance. It can also be judgmental, expressing an expert's subjective assessment. MCA's capacity to handle and apply both types of option evaluation simultaneously is one of its strengths. However, in either instance, the criterion must be described clearly enough to be examined. If assessment at a specific level is difficult, it can be useful to divide a criterion down into a further sublevel of more explicitly specified criteria.

Mutual independence of preferences: Simple implementations of MCA demand that preferences linked with the outcomes of the alternatives be independent of one another from one criterion to the next. The essential premise is straightforward: can you assign preference ratings for alternatives on one criterion without knowing their preference scores on any other? If the response is posotive, this criterion is preferred over the others. The question is then repeated for each of the remaining requirements. If the answer is always yes, the criteria are thought to be mutually preferentially independent. If the sum of weighted averages is to be used to integrate preference scores across criteria, this criterion must be met, and this is true for all MCA techniques, whether they recognize it formally or not.

Preferences are not necessarily incompatible. For example, the satisfaction derived from devouring a trifle may be tied to the proportions in which it is blended rather than the total amount of jelly, custard, sponge, and so on. If this is the case, a simple weighted sum of the amounts of jelly, custard, and so on contained in a set of option trifles would not, in general, represent the individual's preference ranking for the trifles. In practice, the preferable independence question can be handled by asking if the preference scores of an option on one criterion can be awarded independently of knowledge of preference scores on all other criteria for each criterion.

If the response is negative, more complex models for integrating scores across criteria may be required. Two simpler techniques, however, may be possible. The first is to merge two non-preference independent criteria into a single criterion that represents the shared dimension of value. This will be effective if the new criterion is preferred independently of the other criteria. The second method recognizes that options must frequently meet a minimum acceptable level of performance in order to be examined; options that fall below any minimal level are rejected outright because higher performance on other criteria cannot compensate. This barrier usually ensures that the criteria are preference independent; all options fall at or above the minimal level of performance, so that preference on any specific criterion is unaffected by preference on the others. If preference independence is still breached, more sophisticated MCA techniques must be implemented.

Double counting: Decisions in the public sector are especially prone to double counting, especially when it comes to efficacy or advantages. This derives, for example, from a need to define the distribution of effects across the population. As a result, the same basic impact can easily be recorded more than once in a performance matrix. Double counting, like CBA, should be prohibited in MCA because doublecounted effects are likely to be given more weight in the final overall decision than they deserve.

Size: A disproportionate amount of criteria necessitates additional analytical effort in reviewing incoming data and can make analysis communication more challenging. At this point, a final check to ensure that the structure is not larger than necessary is useful. Criteria are explicitly weighted in a thorough application of MCA. However, in the absence of weighting, if there is any possibility of making informal judgements by scanning the performance matrix, it is prudent to ensure that any marked inconsistencies between the number of criteria and the likely importance of the topics they reflect are, if possible, eliminated at this stage. If this is not possible, special care must be made to avoid the imbalance affecting people's interpretation of the matrix.

Impacts occurring over time: Many public-sector decisions entail expenditures that will be made now but will have long-term consequences. Although aggregating all impacts into a single measure can be difficult, with monetary-based strategies, discounting is a fairly well-established procedure for aggregation. There is no one corresponding technique in MCA, however normal discounting of money values can be accommodated in principle, and it can also be applied to physical effect indices other than monetary worth. The reasons behind this are more likely cultural in nature rather than fundamental. Certainly, appropriate decision-facilitating practice would ensure that participants in any decision-making exercise were attracted to time-differentiated impacts and considered how these would be consistently accommodated in the evaluation.

If a target completion date is critical, it can be represented as a distinct criterion with a non-linear value function. Options that are predicted to deliver on time earn high marks, those that are expected to arrive somewhat late receive lower marks, and those that are expected to be significantly late receive zero marks. Many more criteria must be defined in terms of time in order to distinguish between temporary and permanent repercussions. This is typically accomplished by being specific about the time range for which the effects are valued. Time spans may range from criterion to criterion, for example, detecting short-term and long-term health consequences separately.

Another option would be to apply another principle that places less emphasis on long-term effects. Alternatively, other environmentalists prefer techniques that give longer-term repercussions more weight. Finally, an MCA within an MCA might be performed, with expert judgments used to determine the weights to be given to consequences happening in different future time periods. The number of situations where discounting or other analytical approaches to dealing with time-distributed impacts are required in MCA applications is likely to be limited. There is little published guidance on time preference issues in MCA, while John Meyer's chapter in Keeney and Raiffa provides a useful introduction. The most important thing for MCA users to remember is to make sure that all criteria assessments are done on the same basis. Thus, if some impacts are one-time and others are recurrent (perhaps with different sorts of time profile), these distinctions must be explicitly recognized in the scores assigned to alternatives on the relevant criteria.

THE PERFORMANCE MATRIX WITHOUT SCORING AND WEIGHTING

A typical MCA will show the decision maker the performance matrix. The decision maker's role is then to analyze the matrix and reach a conclusion on the ranking of the possibilities, most likely with the assistance of some supplemental advice from those who created the matrix on how the information should be understood. Consumer journals and magazines sometimes offer matrices in this format when comparing items such as electrical products, sports equipment, computer software, or other consumer goods. They are particularly well suited for this purpose because they often address hundreds or thousands of decision makers, each with his or her unique set of objectives.

In performance matrices of this type, the metrics are frequently qualitative descriptions (for example, styling), natural units (such as price or length), or sometimes a rudimentary numerical scale (eg, number of stars), or even a scale of 0 to 100. If the analysis is not to go to the numerical analysis of stages 5 and 6, the use of 0 to 100 numerical scales is not suggested for government applications. The extra work required to create such scales might quickly backfire by sending the intuitive but wrong message that the scores can subsequently be combined together.

Even if the matrix is limited to qualitative descriptions, natural units, and extremely simple scales (such as stars), it is recommended that a similar number of criteria be used within each major sector of the value tree. It is also worthwhile to explore using supplementary data presentations, such as graphics, to encourage individuals to think about the data in new ways and avoid putting disproportionate weight to some elements relative to others.

There are few restrictions and extremely specific recommendations in MCA regarding the maximum and minimum number and types of objectives and criteria that can be set. However, various authors have identified some basic requirements that criteria must meet in order to ensure the reliability and rigor of the analysis (e.g., Keeney and Raiffa, 1976; Roy, 1985; Bouyssou, 1990; Belton and Stewart, 2002; Diakoulaki and Grafakos, 2004; Keeney and Gregory, 2005; Dodgson et al., 2009). These required lists differ significantly since they were created for different MCA methodologies. The following are the most important qualities shared by (nearly) all MCA approaches and must be met by criteria:

• Exhaustiveness: the set of criteria must address all relevant facets of the topic at hand.

• Manageability: To prevent duplicating analytical work, the total number of criteria should be kept as low as feasible, and the value tree of objectives and criteria should be kept as simple as possible.

• Understandability: analysts, decision-makers, problem stakeholders, and all other parties involved in the process must all agree on the assumptions and concepts underlying each criterion.

• Measurability: criteria must quantify an option's performance as exactly and clearly as feasible, numerically or qualitatively, in accordance with the nature of the measure under consideration.

• Non-redundancy: criteria that are extremely similar to others must be removed from the list.

By including only strictly relevant and fundamental criteria, the first two requirements reflect a compromise between the desire to construct a comprehensive value tree that captures all aspects of the problem at hand and the practical need to keep the model relatively simple and not overly costly and time-consuming to use. The understandability requirement imposes the establishment of a common view on the meaning of each criterion and the performance of the associated options (e.g., whether a criterion is defined as a 'benefit condition', and thus needs to be maximized to return a high performance score, or as a 'cost condition,' and thus a low value of performance against that criterion would be preferable). Measurability refers to the ability to express the performance of various options on either a quantitative or qualitative measuring scale using the chosen criteria. Different MCA techniques, however, necessitate varying degrees of precision.

Eventually, the non-redundancy condition is an attempt to minimize double counting concerns (i.e., the inclusion of criteria that account for effects already accounted for elsewhere by other criteria). Such issues are especially common in harsh MCA applications. They also become more difficult to avoid as the number of objectives and criteria in the multi-criteria framework grows. When multidimensional and rather broad notions such as livability and quality of life are included in the multi-criteria framework, they are also likely to result in double-counting of impacts (Anciaes and Jones, 2020).

The illustration below depicts an example of double-counting between criteria, which is common in transportation assessment and evaluation procedures. Different alternative transportation projects are evaluated in this example based on five important objectives: strategic fit, job prospects, air quality improvement, potential environmental dangers, and economic efficiency. The benefit-cost ratio of the projects is used to assess the performance of the project options in relation to the latter goal. On the one hand, this value tree of objectives and criteria tries to include CBA into a multi-criteria framework. The benefit-cost ratio criterion of the choices under consideration, on the other hand, already accounts for various environmental advantages and costs associated with these initiatives. This signals serious double counting issues. A reformulation of the value tree is thus required in this and other similar instances where the inclusion of redundant and overlapping criteria is likely to lead to incorrect interpretations of the pros and drawbacks of the options under consideration.

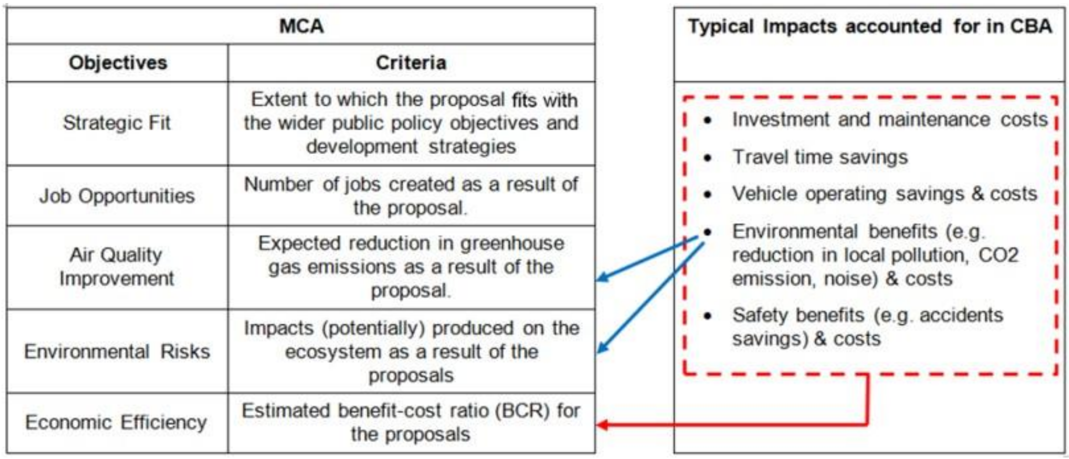


Figure 54: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

3.1.16 Preferential Independence Condition

In order to use a basic weighted additive model to aggregate scores and weights into a global score (in full aggregation MCA approaches), the requirement of mutual preference independence between criteria must be met. When it is not possible to assume mutual preference independence between criteria, the value tree of objectives and criteria must be rewritten, or alternative non-linear and more complex aggregation rules must be utilized (Keeney and Raiffa, 1976; Zeleny, 1982).

The preferences structure and tradeoffs between degrees of performance of any subset of criteria in C are mutually preferential independent if they do not depend on the fixed level of achievement of the other criteria (Belton and Stewart, 2002; Abbas, 2018). In the simplest situation of a decision-making problem with only two criteria C = c1, c2, a feasible subset of criteria is either c1 or c2, and the corresponding complementary subset, which includes the other criteria, is either c2 or c1. In this situation, the preference independence test is carried out by comparing two (hypothetical) choices that perform differently for one of these two criteria but have the same performance level for the other. In general, c1 is said to be preferably independent of c2 if the preference relationship between any two alternatives a1 and a2, which perform differently against c1 but equally against c2, is independent of the set performance level against c2. As a result, if a1 is preferred above a2, the (equal) performance of the two alternatives on c2 has no effect on the preference structure. The above condition can be represented more operationally as follows(Dean, 2022):

$$if\ a_1 > a_2 \rightarrow U(a_1) > U(a_2) \rightarrow u(c_1; c_2)(a_1) > u(c_1; c_2)(a_2)$$

$$if\ c_1\ Pref.\ Ind.\ of\ c_2 \rightarrow (x_1^1;\ \alpha)(a_1) > (x_1^2;\ \alpha)\ (a_2)\ and\ (x_1^1;\ \beta)(a_1) > (x_1^2;\ \beta)\ (a_2)$$

In the above statement, x1 1 and x1 2 represent the performance of the first option a1 and the second option a2 against the criterion c1. This phrase means that (i.e. the performance of the two alternatives versus the criterion c2) can be substituted with any value without changing the preference structure of the two options. In contrast, c2 is said to be preferably independent of c1 if the preference connection between any two options a1 and a2, which differ only in terms of c2, does not rely on a predetermined equal performance level against c1. Assuming, once again, that a1 is chosen over a2, then(Dean, 2022):

$$If\ a_1 > a_2 \rightarrow U(a_1) > U(a_2) \rightarrow u(c_1; c_2)(a_1) > u(c_1; c_2)(a_2)$$

$$If\ c_2\ Pref.\ Ind.\ of\ c_1 \rightarrow (\alpha;\ x_2^1)(a_1) > (\alpha;\ x_2^2)\ (a_2)\ and\ (\beta;\ x_2^1)(a_1) > (\beta;\ x_2^2)\ (a_2)$$

If c1 is preferentially independent of c2 and c2 is preferentially independent of c1, then c1 and c2 are mutually preferentially independent.

In the case of more than two criteria, further rounds of evaluation would be required to demonstrate that any feasible subset of criteria is preferentially independent of its complementary subset (and vice versa for reciprocal preferential independence). For example, in the case of three criterion C = c1, c2, c3, six rounds of evaluation would be required, as shown:

Rounds of Assessment	Possible Subset	Complementary Subset
1	C_1	C_2, C_3
2	C_2	C_1, C_3
3	C_3	C_1, C_2
4	C_2, C_3	C_1
5	C_1, C_3	C_2
6	C_1, C_2	C_3

Figure 55: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

In the first round of evaluation, for example, criterion c1 is said to be preferentially independent of its complementary subsets c2, c3 if the preference relation between any two options a1 and a2, which perform differently against c1 but equally against c2 and c3, is independent of the fixed performance levels against c2 and c3. Assuming that a1 is favored above a2, the (equal) performance of the two alternatives on c2 and c3 has no effect on the preference structure (Dean, 2022).

$$if\ a_1 > a_2 \rightarrow U(a_1) > U(a_2) \rightarrow u(c_1; c_2; c_3)(a_1) > u(c_1; c_2; c_3)(a_2)$$

$$if\ c_1\ Pref.\ Ind.\ of\ \{c_2; c_3\} \rightarrow (x_1^1; \alpha; \beta)(a_1) > (x_1^2; \alpha; \beta)(a_2)\ and\ (x_1^1;\ \delta; \varepsilon)(a_1) > (x_1^2;\ \delta; \varepsilon)(a_2)$$

The above expression shows that α and β (i.e. the performance of the two alternatives against the criteria c2 and c3, respectively) can be replaced by any value and without changing the preference relationship between the two options.

The criteria c2, c3 are then said to be preferentially independent of their complement c1 (round of assessment 4 in Table 9) if the preference relation between any two options a1 and a2, which perform differently against c2, c3 but equally with respect to c1, is independent of the fixed performance level against c1. As a result, if a1 is preferred over a2, the decision-maker will continue to favor a1 over a2 for whatever common performance on c1.

$$If\ a_1 > a_2 \ \rightarrow\ U\,(a_1) > U\,(a_2)\ \rightarrow\ u(c_1; c_2; c_3)(a_1) > \ u\,(c_1; c_2; c_3)(a_2)$$

$$If\ \{c_2; c_3\}\ Pref.\ Ind.\ of\ c_1 \rightarrow (\alpha; x_2^1; x_3^1)(a_1) > (\alpha; x_2^2; x_3^2)(a_2)\ and\ (\beta; x_2^1; x_3^1)(a_1) > (\beta; x_2^2; x_3^2)(a_2)$$

If c1 is preferably independent of c2, c3, and c2, c3 are selectively independent of c1, the two subsets c1 and c2, c3 are mutually preferentially independent.

There appear to be various differences on the actual consequences of violating this condition. While many authors (e.g., Keeney and Raiffa, 1976; Beroggi, 1999; Belton and Stewart, 2002; Abbas, 2018) emphasize the importance of thorough criteria selection and the need to always perform the preferential independence test, others claim that violations of this condition only result in minor measurement errors (e.g., Weiss and Weiss, 2009). It is also argued that the favored independence test can be readily circumvented by using monotonic value functions for criterion performance (Edwards, 1977; Weiss and Weiss, 2009) or by using threshold values on criteria (Dodgson et al. 2009). Whatever the truth of these statements, it is evident that in the absence of a careful assessment of whether reciprocal preference independence between criteria holds, the findings obtained by using a basic weighted additive model must be taken (at least) with a grain of contempt.

JUDGEMENTS BETWEEN OPTIONS WITHOUT SCORING AND WEIGHTING

It is difficult to determine in what extent a performance matrix alone allows the comparison of options. What is maybe equally crucial is to be explicit about which types of comparisons are prohibited and why.

Dominance

In the beginning the set of possibilities can be examined to determine the presence of dominance. One option outperforms another if it performs at least as well on all criteria and is clearly superior on at least one. Assuming that all of the criteria score estimates are correct, if option A dominates option B, then B cannot be the greatest option available.

As a consequence, if the MCA's goal is to recommend a single best alternative, B may be eliminated from consideration. If the goal is short-listing, it is possible, although unusual, that a dominated alternative will advance to the next step of the selection process. Logically, this would only make sense if it was anticipated that new information about options would emerge, that some of the criteria scores would be incorrect, or that the dominant option (A) would become unavailable.

Being dominated may disqualify an option from further examination in screening, depending on the number of options required for later review and the strength of the others available, but dominance just states that B must rank lower than A. Finally, dominance is a transferable property. If A dominates B and B dominates C, A will always dominate C, and this dominance does not need to be tested explicitly. In practice, dominance is uncommon. It can only help to differentiate between possibilities and so support genuine decisions to a limited extent.

Assessing performance levels (with scoring)

The first consideration in developing consistent numerical scales for evaluating criteria is to ensure that the feeling of direction is consistent in all circumstances, so that (typically) higher levels of performance correspond to higher value scores. This could indicate a reversal of the natural units. Access to a facility, for example, could be measured in terms of distance to the nearest public transportation, where the natural scale of measurement (distance) links a low number with good performance. It is customary to provide a value score between 0 and 100 on an interval scale to each condition.

The benefit of an interval scale is that differences in scores are consistent within each criterion, though it does not allow for the conclusion that a score of 80 represents a performance that is five times as good as a score of 16 (which would require a ratio scale of measurement). The 'law' that the scoring scale symbolizes is only valid inside the constraints of this specific MCA. However, when combined with suitably calculated relevance weights for the criteria, the use of an interval scale measurement allows for the pursuit of a comprehensive MCA.

The first stage in developing an interval scale for a criterion is to identify the levels of performance that correspond to any two reference points on the scale, which are typically 0 and 100. One option (global scaling) is to assign a score of 0 to represent the worst level of performance expected to be encountered in the broad type of decision problem currently being addressed, and a score of 100 to indicate the best level. Another option (local scaling) associates 0 with the option in the currently evaluated set of alternatives that performs the least well and 100 with the one that performs the best.

The distinction between local and global should have no bearing on the ranking of options. Global scaling has the advantage of more easily accommodating new alternatives at a later stage if these record performances that differ from those of the initial set. However, it has the disadvantage of requiring extra, not always helpful judgments in defining the scale's extremes, and, as will be seen in the following chapter, it lends itself less easily to the formulation of relative weights for the various criteria than local scaling.

Once the end points for each criterion are determined, there are three ways to assign scores to the options:

1. The first of these employs the concept of a value function to convert a measure of accomplishment on the criterion in question into a value score on a scale of 0 to 100. For example, if one criterion relates to the number of regional full-time employment produced and the minimum likely level is 200 and the maximum 1,000, a simple graph can be used to convert the natural scale of measurement to the 0 - 100 range necessary for the MCA.
2. Direct rating is the second way of assessing performance on an interval scale. This is employed when there is no universally agreed-upon scale of measurement for the criterion in question, or when neither the time nor the resources are available to conduct the measurement. Direct rating simply associates a number in the 0-100 range with the value of each choice on that criterion by using an expert's judgment. Because these scores are being assessed on an interval scale of measurement, correlations between the variations

in the scores of the possibilities do have value, and it is crucial to ensure that the assessments made are consistent in this regard.

A difference of (for instance) 20 points, for example, should reflect an improvement in rated value that is exactly half that reflected by a difference of 40 points. The use of direct rating judgements in MCA can cause some consistency issues when the method is to be used by various people, such as when some decision-making authority is outsourced to regional offices. The most basic technique to foster consistency is to present a set of examples or scenarios with suggested scores.

Another consideration with direct rating is that people with the greatest qualified expertise to make the decisions may also have a vested interest in the decision's outcome. When this is the case, there is always the risk that their rating assessments will be influenced (possibly unintentionally) by variables other than the performance of the options on the criterion being evaluated. Ideally, such decisions should be made by individuals who are both knowledgeable and unbiased. If this cannot be avoided, it is critical to be aware of the possibility of bias sneaking in and, for example, to apply sensitivity testing to the scores at a later stage to ensure the robustness of the analysis's outcome.

3. A third technique to assessing the value of options on a criterion is to address the issue indirectly, by eliciting a series of verbal pairwise assessments from the decision maker expressing their assessment of the performance of each option compared to each of the others. The Analytic Hierarchy Process (AHP) does this, as do REMBRANDT and MACBETH (e.g., Bana e Costa and Vansnick, 1997; Bana e Costa et al, 1999).

The MACBETH process, for example, invites decision makers to rate the attractiveness difference between each pair of alternatives as one of:

- C1 very minor change
- C2 minor difference
- C3 difference is moderate
- Significant change in C4
- Significant change in C5
- C6 extreme distinction

After doing all of the required pairwise comparisons, a series of four computer programs processes the data to create a set of scores for the alternatives on a 0-100 scale that are mutually consistent with the full set of specified pairwise assessments. If there are inconsistencies in the judgments, as can happen, and a compatible set of scores cannot be computed from them, the programs lead the decision maker through procedures to change the inputs until consistent scores are achieved.

Multi-criteria decision analysis MCDA

Multi-criteria decision analysis, or MCDA for short (also known as multi-attribute decision analysis, or MADA), is a type of MCA that has found many uses in both public and private sector organizations. This chapter defines MCDA and then describes what is required to do such an analysis.

MCDA is a methodology as well as a set of approaches that aim to provide an overall ranking of possibilities, from most preferred to least favored. The amount to which the options meet various objectives may differ, and no single option will clearly be the best at achieving all objectives. Furthermore, there is usually some conflict or trade-off between the objectives; for example, more desirable solutions are frequently more expensive. Costs and advantages frequently clash, but so can short-term rewards versus long-term benefits, and risks may be higher for the otherwise more favorable options.

MCDA is a method of approaching complex problems with a mix of monetary and non-monetary objectives, breaking the problem down into more manageable pieces to allow data and judgments to be applied to the pieces, and then reassembling the pieces to present a coherent overall picture to decision makers. The goal is to aid in thinking and decision making, not to make the decision. MCDA, as a collection of methodologies, provides several methods for disaggregating a complicated problem, measuring the amount to which choices achieve objectives, ranking the objectives, and reassembling the pieces. Luckily, numerous user-friendly computer applications have been developed to aid with the technical components of MCDA.

Keeney and Raiffa presented the first comprehensive presentation of MCDA in 1976, and their book is still valuable today. They expanded on decision theory, which is commonly connected with decision trees, uncertainty modeling, and the anticipated utility rule. Keeney and Raiffa developed a theoretically valid integration of the uncertainty associated with future consequences and the various aims such consequences realize by extending decision theory to allow multi-attributed consequences. The primary assumption underlying decision theory is that decision makers want to make intelligible decisions. That is, decision-makers would not purposefully make decisions that contradict each other. No one would lay multiple bets on the outcome of a single race, knowing that no matter which horse won, they would lose money.

The theory expands on the concept of coherence, or consistency of preference, and proposes some simple principles of coherent preference, such as the principle of transitivity: if A is more favorable than B and B to C, then A should be preferred to C, which is required if preference is to be expressed numerically. It is possible to prove non-obvious theorems that are effective decision-making guides by taking these very clear concepts as axioms. Geometry is a study that has a parallel.

Between coherent preference and number systems, a logical equivalence is established. If preferences are consistent, two types of metrics emerge logically: probability and utility, both of which are concerned with the outcomes of decisions. The first theorem demonstrates the existence of probabilities, which are numbers that represent the possibility that certain outcomes will occur.

The second theorem establishes the existence of utilities: numbers that indicate the subjective value of the result and the risk attitude of the decision maker. The third theorem provides a decision-making guide: take the option with the greatest sum of probability-weighted utility. Keeney and Raiffa expanded the set of axioms to allow for the analysis of decisions with multiple objectives. In practice, MCDA is used to assist decision makers in developing consistent preferences. In other words, while coherent preferences are not expected to begin with, the technique assists individuals and groups in achieving reasonably coherent preferences within the context of the problem at hand. Decisions can be made with greater certainty if consistent preferences have been established.

3.2 Stages in MCDA

MCDA can be used either retrospectively to evaluate things that have already been assigned funding, or proactively to evaluate those that have yet to be suggested. As a result, there is no need to discriminate between these two uses in the subsequent MCDA explanations, even though the technique will be realized differently in practice. MCDA can be used either retrospectively to evaluate things that have already been assigned funding, or proactively to evaluate those that have yet to be suggested. As a result, there is no need to discriminate between these two uses in the subsequent MCDA explanations, even though the technique will be realized differently in practice. Some of the process is technical, but equally crucial is organizing the correct individuals to help at each stage, as well as some social suggestions. A simple MCDA example will be used to demonstrate the phases involved in selecting a toaster for Fred Jones' family. This simple choice problem would hardly necessitate a comprehensive MCDA, but it does provide an illustration free of the complexities and challenges encountered in real-world applications.

The use of weights provides two types of difficulty. One is the requirement for extreme caution in order to establish logical consistency in the construction of weights and scores. In some circumstances, the additional obstacle is dealing with the vastly disparate value judgments of diverse contributors. **Applying MCDA: Detailed Steps:**

1. **Establish the decision context.**
   1.1 Establish aims of the MCDA, and identify decision makers and other key players.
   1.2 Design the socio-technical system for conducting the MCDA.
   1.3 Consider the context of the appraisal.
2. **Identify the options to be appraised.**
3. **Identify objectives and criteria.**
   3.1 Identify criteria for assessing the consequences of each option.
   3.2 Organise the criteria by clustering them under high-level and lower-level objectives in a hierarchy.
4. **'Scoring'. Assess the expected performance of each option against the criteria. Then assess the value associated with the consequences of each option for each criterion.**
   4.1 Describe the consequences of the options.
   4.2 Score the options on the criteria.
   4.3 Check the consistency of the scores on each criterion.
5. **'Weighting'. Assign weights for each of the criterion to reflect their relative importance to the decision.**
6. **Combine the weights and scores for each option to derive an overall value.**
   6.1 Calculate overall weighted scores at each level in the hierarchy.
   6.2 Calculate overall weighted scores.
7. **Examine the results.**
8. **Sensitivity analysis.**
   8.1 Conduct a sensitivity analysis: do other preferences or weights affect the overall ordering of the options?
   8.2 Look at the advantage and disadvantages of selected options, and compare pairs of options.
   8.3 Create possible new options that might be better than those originally considered.
   8.4 Repeat the above steps until a 'requisite' model is obtained.

Figure 56: **source: Dept. Communties & Goverment. (2009). Multi-criteria analysis: a manual. www.communities.gov.ukcommunity,opportunity,prosperity:**

ESTABLISHMENT OF MCDA's AIMS AND IDENTIFICATION BY THE DECISION MAKERS & OTHER KEY PLAYERS

As an MCDA continues, new features and concerns are frequently disclosed, which may indicate a modification or shift in goals. Still, the MCDA must begin somewhere, and a statement of beginning goals is critical to developing the subsequent stages. After all, MCDA is about establishing the extent to which options produce value by meeting objectives, and at this point, you have two choices: do the MCDA or not. Choosing to perform the MCDA indicates that someone deemed the analysis to be more valuable than not performing it. Clarity about the MCDA's goals aids in the definition of tasks for later phases and keeps the analysis on track.

The first impact of these goals on the MCDA is the selection of essential players to participate in the analysis. A crucial player is somebody who can make a significant and beneficial contribution to the MCDA. All of the significant perspectives on the subject of the analysis are represented by key participants. One critical viewpoint is that of the final decision maker and the body to whom that person is accountable, because the values of their organization must be expressed in the MCDA. These individuals are frequently referred to as stakeholders, as they have an involvement, economically or otherwise, in the outcomes of any decisions made. They may not participate physically in the MCDA, but their beliefs should be reflected by one or more prominent people who do.

There's no MCDA that is ever limited just to the perspectives of stakeholders. Other essential people join because they have knowledge and skill on the subject. This comprises both internal and external experts, as well as persons who have no stake in the final decision yet have information that can help the analysis. The MCDA's designers will need to determine which stakeholders and other key players should be involved, as well as the amount to which they should participate in the analysis.

DESIGNING THE SOCIO-TECHNICAL SYSTEM FOR CONDUCTING THE MCDA

What MCDA format will be utilized, and how will it be implemented? That is the technical side of things. The two are designed to work together to guarantee that they achieve the MCDA's goals. An MCDA, for example, to support a major decision, such as the placement of a new airport, will be broad, including numerous objectives and criteria and involving many interest groups and key stakeholders. The model's complexity will impact who contributes in part, and the views expressed by interest groups and significant players will influence the model's complexity. An MCDA to prioritize proposed projects within a governmental unit, on the other hand, will include few if any outsiders and will use a simpler type of MCDA. There is no such thing as the 'best' design. The social and technological components of the MCDA system must be studied concurrently.

A common strategy to problem solving in the civil service is to convene a series of meetings interspersed with staff work, which continues until the assignment is completed. However, one advantage of MCDA is that it allows for more cost-effective designs than the traditional technique. There are other approaches that can be taken (for example, assisted workshops).

CONSIDERATION OF THE MCDA'S CONTEXT

Addressing the existing condition and then being specific about the aims to be reached establishes the gap between now and the future vision, which clarifies the role of the MCDA. That vacuum will presumably be filled by people authorized to make decisions and allocate resources to help reach the future state. The analysis might be framed in a variety of ways, some more directly supporting the final result than others. The MCDA could be designed to:

- Demonstrate the best path ahead to the decision maker
- Identify areas of greater and lesser opportunity
- Sort the options according to their importance.
- Explain the distinctions between the possibilities.
- Assist key stakeholders in better understanding the issue.
- Identify the optimal allocation of resources to achieve the goals.
- Facilitate the production of new and better solutions.
- Improve communication between isolated portions of the organization, or
- Any combination of the above.

A SWOT analysis, which considers strengths, weaknesses, opportunities, and threats, is particularly useful in formulating options. Participants can be encouraged to develop options that will build on strengths, address weaknesses, seize opportunities, and minimize dangers while keeping in mind that options are intended to fulfill the goals.

Other context factors include the larger political, economic, social, and technological (PEST) contexts in which the analysis will be carried out. Scenario analysis of how major PEST features can evolve in the future, affecting the capacity of suggested alternatives to attain the intended future state, can occasionally encourage key actors to develop options and examine objectives that would otherwise have been overlooked. Scenario analysis39 can also assist participants in acknowledging future uncertainty and, as a result, making assumptions about outcomes more clear, focusing attention to ramifications that might otherwise be missed.

IDENTIFICATION OF THE OPTIONS TO BE APPRAISED

Options are frequently developed on a go/no-go basis. Project finance is frequently done in this manner. There is, however, an option. Bids might be solicited to specify the benefits achieved at various levels of funding. Then, some bids can be completely rejected, while others can be funded at lower levels and others at full levels. This allows financing decisions to be made in a more cost-effective manner. This method, even so, is only effective if individuals asking for funds have a pretty clear understanding of the fundamental objectives, or the value that those giving the cash aim to create. In all circumstances, whether the alternatives are provided or must be produced, individuals performing the MCDA should be willing to amend or add to the options as the analysis develops.

IDENTIFICATION OF THE CRITERIA FOR ASSESSING THE CONSEQUENCES OF EACH OPTION

Assessing alternatives necessitates consideration of the options' implications, because it is those outcomes that are being evaluated, not the options themselves. Consequences differ in a variety of ways, and those that are important because they achieve goals are referred to as criteria or qualities. Criteria are clear and measurable goals.

Criteria express the various ways in which options provide value. If options are already provided, a 'bottom-up' approach to identifying criteria is to explore how the possibilities differ from one another in meaningful ways. A 'top-down' method is to inquire about the goal, purpose, mission, or general objectives that must be met. Overall goals are sometimes stated. The DETR's new approach to evaluating transportation investments outlines the following high-level objectives for transportation schemes:

- To safeguard and improve the built and natural environment.
- To increase the safety of all travelers.
- To contribute to an efficient economy and to support long-term economic growth in appropriate regions
- To improve access to everyday facilities for all, particularly those without a car, as well as the integration of all modes of transportation and land use planning, resulting in a better, more efficient transportation system.

These are further subdivided into criteria, some of which may be numerically measured, including monetary valuation, some can be rated, and some can only be described qualitatively. Identifying criteria necessitates taking into account the underlying reasons for the organization's existence as well as the key ideals that the organization supports.

ORGANIZATION OF THE CRITERIA BY CLUSTERING THEM UNDER HIGHER-LEVEL AND LOWER-LEVEL OBJECTIVES IN A HIERARCHY

Arranging the criteria and objectives in this manner makes it easier to score the options on the criteria and examine the overall results at the objective level. At the top of the hierarchy is the most essential trade-off between the objectives. This is frequently a trade-off between costs and advantages. Thus, the ultimate goal is the whole result, taking into consideration both costs and benefits. The next step down would include expenses as one goal and benefits as another. expenses could then be divided into monetary and non-monetary expenses, as well as short-term and long-term, capital and operating, or any other differentiation that reflects greater friction between the objectives. The same is true for perks. Top-level trade-offs aren't necessarily about balancing costs and rewards. Other alternatives include risks against advantages, customer benefits versus supplier benefits, long-term benefits versus short-term benefits, and so on. A value tree is a common name for this hierarchical form.

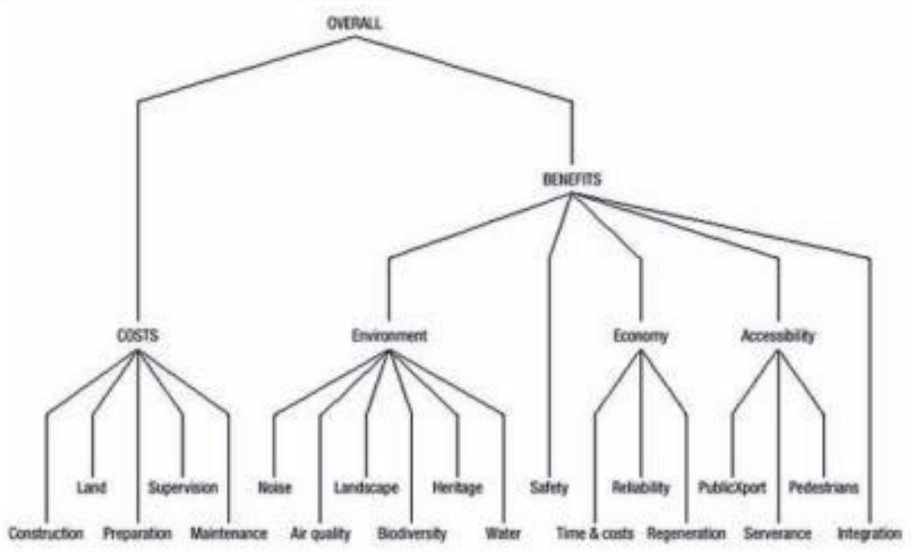


Figure 57: Source: Dept. Communties & Goverment. (2009). Multi-criteria analysis: a manual. www.communities.gov.ukcommunity, opportunity, prosperity)

The diagram above depicts how the DETR's new approach to evaluating transportation investments' objectives and criteria might be depicted.

The five objectives have been grouped under the higher-level objective 'BENEFITS,' and the cost of the investment has been separated from the 'Economy' objective and displayed as a separate objective, with its sub-costs expressed as criteria beneath. This split makes it easier to demonstrate advantages vs costs for schemes that are being evaluated. Because 'Safety' and 'Integration' have no sub-objectives, they also act as criteria. This representation is only for illustrative purposes; if MCDA is used, it may need to be modified.

Combining the objectives and criteria in a value tree frequently reveals the conflict among the objectives, which can lead to their definitions being refined. Making the value tree explicit and visible may encourage new possibilities for reducing apparent conflicts between the objectives. Iterating back to earlier phases is common in any MCDA.

DESCRIPTION OF THE CONSEQUENCES

The simplest method is to provide a basic qualitative description for each alternative while considering each criterion. For simpler issues, use the previously defined performance matrix. For complex situations involving a value tree, it may be essential to create a distinct consequence table for each alternative, similar to the Appraisal Summary Table for the DETR's new approach to transport investment appraisal. A table like this is built similarly to a value tree, with separate columns (or rows in the case of the DETR summary table) for each condition. The bottom row usually contains the performance metrics for that choice based on the column's criterion. Throughout the table, higher level objectives are displayed in rows above the subsidiary criteria.

SCORING THE OPTIONS ON THE CRITERIA

The basic idea is to create scales that express preferences for the consequences, weight the scales based on their relative relevance, and then compute weighted averages across the preference scales. These are basic scales with the most and least desired options on a criterion at their endpoints. The most favored option receives a preference value of 100, while the least preferred receives a score of 0, similar to the Celsius scale of temperature. The other selections are given scores, and the discrepancies in the numbers show the level of preference. These are relative judgments that compare differences in outcomes, and they are frequently easier for individuals to make than absolute judgments. Modeling, such as that used in cost-benefit analysis, can be utilized for some criteria to aid in the process of turning outcomes into comparative scores.

The difference-scaling method yields numbers that represent relative preference strength. This type of metric expresses the value associated with the option's impact on a specific criterion. Because 'value' is generally perceived to suggest primarily financial value, the phrase'strength of preference' is employed here instead. 'Strength of preference' should not be confused with 'preference.' Remember that coherent desire logically entails two measurable values, probabilities and utilities, in decision theory.42 Thus, if their values are similar, A may be favored over B since A is more likely. If preference is merely used as a measure of value, then A and B must be regarded to be equally viable choices. In the event they are not, the uncertainty associated with A and B must be addressed in another way, such that strength of preference metrics simply indicate relative value.

Relative scaling is especially useful for comparing multiple options offered at the same time. However, possibilities are sometimes evaluated serially, requiring comparison to a standard. In these situations, using fixed scales is frequently beneficial. The zero point for a specific scale on a certain criterion could be established as the lowest allowable number - any choice scoring less would be rejected outright regardless of its scores on other criteria. The 100-point limit might be specified as the maximum achievable - this would necessitate creating and specifying a hypothetical top-scorer alternative.

CHECKING THE CONSISTENCY OF THE SCORES ON EACH CRITERION

This phase is normally completed during the scoring process, however it is presented here separately to emphasize its significance. The procedure for determining consistency is determined by the type of scale employed. The strategy for the relative scales used in this chapter is to compare differences on a particular scale. If the scale was properly developed, comparing differences should have been part of the scoring process, so the scale should be consistent. Consistency of preferences is a virtue in MCDA, and it helps to secure reliable outcomes. Initial scoring often exposes irregularities, both within and between criteria. Several repetitions may be required until the key players are satisfied that their preferences are consistent enough. The technique known as modeling genuinely assists people in achieving their goal; consistency is not essential to begin.

WEIGHTING THE CRITERIA IN ORDER TO REFLECT THEIR RELATIVE IMPORTANCE TO THE DECISION

The preference scales are nevertheless incompatible because a unit of preference on one does not always equal a unit of preference on the other. Equating the units of preference is formally similar to determining the relative importance of the scales, therefore the process is relevant to individuals making the decisions with the correct weighting mechanism.

To elicit weights for the criteria, most MCDA proponents currently employ the'swing weighting' approach. This is based on comparisons of differences: how does the swing from 0 to 100 on one preference scale compare to the swing from 0 to 100 on another? Assessors are advised to consider both the gap between the least and most desired options, as well as how much they care about that difference, when making these comparisons. There is a significant distinction between measurable performance and the value of that performance in a given environment. Improvements in performance may be genuine, but they are not always helpful or highly valued: an increase in additional performance may not result in an increase in added value.

Thus, the weight assigned to a criterion indicates both the range of difference between the possibilities and the importance of that difference. As a result, it is possible that a criterion popularly regarded as'very important,' such as safety, will have a similar or lower weight as another comparatively lesser priority criterion, such as maintenance expenses. This would occur if all of the solutions had roughly the same level of safety but vastly different maintenance costs. Weights can be any number as long as their ratios consistently indicate the valuation of the variations in preferences between the top and bottom scores (whether 100 and 0 or other numbers) of the scales being weighted.

The swing weighting method can be implemented with a group of significant players utilizing a 'nominal-group strategy.' First, the criterion with the greatest preference swing from 0 to 100 is identified. If the MCDA model simply includes a few criteria, the biggest swing may usually be discovered fast with participant agreement. With multiple criteria, a paired-comparison method may be required: compare criteria two at a time for their preference swings, always retaining the one with the larger swing to be compared to a new criterion.

The criterion that emerges from this procedure with the greatest swing in preference is given a weight of 100 and becomes the standard against which all others are tested in a four-step process. First, any other criterion is picked, and all participants are asked to write down a weight that reflects their assessment of its swing in preference compared to the standard, without discussionIf the criterion, for example, is assessed to reflect half the swing in value as the standard, it should be given a weight of 50. Second, individuals reveal their judged weights to the group (for example, by a show of hands against weight ranges such as 100, 90s, 80s, 70s, and so on), and the findings are recorded on a flip chart as a frequency distribution. Third, individuals who supplied extreme weights, both high and low, are asked to explain why, and a broad group discussion ensues. Fourth, after hearing the discussion, a subset of participants determines the final weight for the criterion.

Typically, the subset consists of the decision maker, those representing the decision maker, or those participants (typically the most senior ones) whose perspectives on the issues allow them to take a broad picture, allowing them to comprehend the potential tradeoffs among the criteria. Thus, the final weights are informed by a group debate that began with the awareness of where everyone stood, uninfluenced by others. The process also involves others closest to the accountable decision maker in making decisions that are solely the responsibility of that person, whether or not they are expressed numerically.

The assignment of weights raises the question of whose choices are most important. However, it should be highlighted that a generally satisfactory criterion that appears to underpin many CBA valuations is that they should reflect the informed preferences of the general public, to the extent that these preferences and the relative weight of the criteria can be articulated numerically. This is frequently a good goal for MCDA. However, it is possible that this is not an aim shared, at least initially, by all persons who may expect to be consulted about a certain application. The procedure of calculating weights is thus critical to the efficacy of an MCDA. They are frequently derived from the opinions of a group of people. They could represent a face-to-face gathering of key stakeholders or those able to explain those stakeholders' viewpoints, in which weights are derived individually, then compared, with time for contemplation and change, followed by broad consensus. If there is no agreement, it may be desirable to move two or more sets of weights ahead in parallel, because agreement on option choice can often be reached even without agreement on weights. While this does not easily lead to consensus, explicit awareness of the various weight sets and their effects might aid in the subsequent search for an acceptable compromise.

Despite these limitations, the meaning of weights in MCDA is generally obvious and straightforward. With other MCA approaches, the concept of a 'weight' takes on other connotations. It must always be handled with caution.

CALCULATION OF THE OVERALL WEIGHTED SCORES AT EACH LEVEL IN THE HIERARCHY

This is a task for computers, while a calculator can be used in some cases. Each option's total preference score is simply the weighted average of its scores on all criteria. Using sij to represent the preference score for option i on criterion j and wj to indicate the weight for each criterion, the total score for each choice, Si, is given by (Dept. Communties & Government, 2009):

$$S_i = w_1s_{i1} + w_2s_{i2} + \ldots + w_ns_{in} = \sum_{j=1}^{n} w_js_{ij}$$

In other words, multiply an option's score on a criterion by the important weight of that criterion, then total the products to get the overall preference score for that choice. Then, for the remaining alternatives, repeat the process.

CALCULATION OF THE OVERALL WEIGHTED SCORES

According to MCDA theory, the basic weighted averaging computation shown above is only justifiable if one condition is met: all criteria must be mutually preference independent. This is a simple concept, less limiting than real-world independence or statistical independence. It means that the preference scores assigned to all alternatives on one criterion are unaffected by the preference scores assigned to all options on the other criterion. Some examples might be useful. In the actual world, two criteria can be causally linked, resulting in statistical correlation between the scores on the two criteria, while being preference independent.

If mutual preference independence is not detected when the criteria are set, it is frequently recognized when scoring the options. When an assessor states that he or she cannot rate the preference scores on one criterion without knowing the scores on another, preference dependence has been identified. This is frequently due to double counting; if two criteria truly signify the same thing but have been expressed in seemingly distinct ways, then when the scores are elicited, the assessor will frequently revert back to the first criterion while assessing the second. This is a hint to look for a solution to merge the two criteria into a single one that encompasses both meanings.

Mutual preference independence can fail when one or more options perform so poorly on a given criterion that scores on other criteria are insufficient to compensate. This provides the advantage of restoring the remaining options' mutual preference independence. If that is not possible, MCDA can nonetheless handle the failure by employing slightly more complex mathematics, typically involving multiplicative factors in addition to the simple weighted average model described in this section.

If either of the two numbers multiplied together is low, the total preference is low; this feature of the model is non-compensatory. However, for most government applications, especially when fixed scales are utilized and the lowest position is designated as the minimum permissible, value above the minimum is additive, therefore the simple compensatory model suffices.

EXAMINATION OF THE RESULTS: AGREE THE WAY FORWARD OR MAKE RECOMMENDATIONS

The weighted average of all preference scores determines the top-level ordering of alternatives. These total ratings also indicate how much superior one alternative is than another. As a result, if the total scores for alternatives A, B, and C are 20, 60, and 80, respectively, the difference in overall strength of preference between A and B is twice that of B and C. Another, slightly cumbersome, way to explain this is that, as compared to B, A is twice as unfavorable as C.

Moving down a level in the value tree and displaying the options in a two-dimensional plot to indicate the main trade-offs is another excellent way to display overall outcomes. If the next step down is costs and benefits, then a graph of benefits versus costs might be illuminating, as it effectively presents a relative value-for-money image. The most cost-effective solutions are on the plot's outside edge. Options on the outside are said to 'dominate' options on the inside because they are both more advantageous and less expensive.

An MCDA can produce unexpected outcomes that must be considered before making judgments. To deal with unexpected outcomes and examine the consequences of new perspectives provided by the MCDA, it may be essential to build a temporary decision system. This interim method is made up of a series of working meetings that result in recommendations to the final decision-making body. Participants in the working meetings are tasked with reviewing the MCDA results, validating the findings for validity, considering the implications for the organization, and developing recommendations for the next steps.

When MCDA produces unexpected results, it is tempting to dismiss the post-MCDA stage, dismiss the analysis, and find another basis for making judgments. However, it is critical to recognize that if inconsistencies between MCDA results and people's intuitions are not investigated, the MCDA model was not "required." 43 Exploring the differences will not make the concern go away; on the contrary, it may increase if the MCDA is determined to be sound but the message it conveys is unpleasant or undesired. Working through the results ensures that subsequent decisions be made fully informed of the potential ramifications.

CONDUCTION OF SENSITIVITY ANALYSIS: HOW DO OTHER PREFERENCES OR WEIGHTS AFFECT THE OVERALL ORDERING OF THE OPTIONS?

Sensitivity analysis examines the amount to which ambiguity about inputs or conflicts between persons affect the final overall outcomes. The selection of weights can be contentious, especially when evaluating schemes or initiatives of public interest. MCDA has been shown to assist decision makers in reaching more satisfactory answers in various instances.

Primarily, stakeholder and key player groups can be contacted to verify that the MCDA model incorporates criteria that are important to all stakeholders and key players. Second, interest groups frequently dispute on the relative importance of the criteria and some scores, albeit weights are frequently more contentious than scores. Using the model to explore how the ranking of options changes under different scoring or weighting systems reveals that two or three options always come out best, even if their order changes.

Accepting a second-best option can be demonstrated to be linked with little loss of overall benefit if the variations between these best options under different weighting methods are minor. This is frequently not obvious in the ordinary thrust of dispute between interest groups since they focus on their differences while ignoring the many criteria on which they agree. Third, sensitivity assessments can start to identify methods to improve options. Sensitivity analysis has the potential to be effective in resolving differences between interest groups.

LOOKING AT THE ADVANTAGES AND DISADVANTAGES OF SELECTED OPTIONS, AND COMPARISON OF THE OPTIONS' PAIRS

Many analysis can be performed to gain a better understanding of the concerns raised by the MCDA. These further analyses are easily carried out with the assistance of computer programs developed to perform MCDA; more on the tools and analyses may be found in the results chapter. In addition to automatically drawing graphs like the ones shown above, these tools allow users to rapidly determine the benefits and drawbacks of each option and compare them.

A high score on a strongly weighted criterion is an advantage; a high score on a somewhat unimportant criterion isn't an advantage because it doesn't contribute to overall preference. A poor score on an important criterion is a disadvantage. Disadvantages matter because they lower total preference, but low scores on irrelevant criteria do not. Understanding the benefits and drawbacks helps to identify areas where solutions could be improved.

Comparing choices is especially relevant when one option is by definition a standard. Large variations in preference ratings between pairs of options on critical criteria can be recognized fast, assisting in the development of new and better options. Another useful comparison is between the option with the highest benefit score and the option with the lowest cost.

CREATING POSSIBLE NEW OPTIONS THAT MIGHT BE BETTER THAN THOSE ORIGINALLY CONSIDERED

The major distinctions between the two options may indicate how to generate a new option. For example, comparing the most advantageous option to the least advantageous option may reveal how to develop a new option that has many, but not all, of the advantages of the most advantageous option while being less expensive. This is sometimes accomplished by lowering the benefits, and hence the cost, of criteria that do not carry much weight. Reducing the cost in this manner may more than compensate for the loss of benefit, providing a viable choice that is not overly expensive.

If new options are generated, they should be added to the list of possibilities and scored on all criteria. If relative scaling was used and the new choice is least desired on some criteria and most preferred on others, it is easier to assign scores less than 0 or more than 100, so that weights do not need to be modified. An important aspect of MCDA is that if the new choice gives no information about the existing options and criteria, nothing that has previously been completed must be modified. It is just essential to add one extra preference score to each criterion.

REPETITION OF THE ABOVE STEPS UNTIL A 'REQUISITE' MODEL IS OBTAINED

A requisite, meaning necessary, model is one that is only adequate for resolving the difficulties at hand. When time is limited and resources are scarce, less work should be done on minor problems of minor relevance. The Joneses' toaster analysis was more than necessary, yet it taught them some surprising facts. Many firms waste valuable time acquiring information, refining inputs, and modeling. "Will this activity, whatever its outcome, make any difference to a decision?" is a critical question to ask of any activity that is part of an analysis. If not, the activity is not worthwhile.

One notable feature of MCDA models is that they are typically extremely insensitive to a wide range of scores and weights. This is easily proved via sensitivity analysis, but individuals typically find it difficult to live with rough-and-ready inputs until they have experienced this insensitivity. "Come back in six months after we've gathered more data," is a common response to the proposal that an initial MCDA will serve to indicate what data important, and that sensitivity analysis will expose the tolerance of findings to significant imprecision in many of the inputs. Many people have worked with models where precision is critical.

Imprecision is tolerated so effectively in MCDA models because the scores on many of the criteria have substantial statistical correlation, and so the weights on those criteria can be allocated in any way among the correlated criteria. Furthermore, changes in scores on individual criteria are sometimes overshadowed by scores for the same options on other criteria. As a result, the structure of any model with several criteria causes this lack of sensitivity. Models get simpler and more necessary as MCDA experience grows.

3.3 Scoring Techniques

The performance of the alternatives against the many criteria is expressed in various units of measurement based on Dr. Dean's Technical Report "A Practical Guide to Multi-Criteria Analysis." These values can be readily transformed to a common scale by means of performance scores to make these performances comparable and to execute the necessary mathematical operations for analyzing and ranking options.

Performance scores are pure numbers (with no physical unit associated) that represent the degree to which the solutions under consideration achieve the various objectives. Although scores are assigned based on data and information about the expected (in the case of ex-ante appraisal exercises) or actual (in the case of ex-post evaluation exercises) impacts of the options, this step inherently includes some subjectivity in the examination and judgment of these impacts. A very arbitrary decision is also made on the kind and width of the scale used to assess the performance of choices.

Indeed, whereas in MAUT and many other formal MCA methods, performance scores are typically measured on an interval scale ranging from 0 (worst performance) to 1 (best performance), for simplistic MCA applications several ordinal and Likert-type scales (e.g. a 0 to 10 scale, a 0 to 100 scale, or a -5 to 5 scale) are commonly used. Furthermore, scores can be assigned using a variety of techniques with varying degrees of complexity and rigor. The following are some of the most prevalent scoring techniques.

3.3.1 Direct Rating Approach

When time and resources to do the analysis are limited, unsophisticated and rough MCA applications will frequently use a direct rating technique to score. Scores are based solely on the value assessments of analysts and decision-makers in this technique. High-performing options receive high ratings, while low-performing options receive lower ratings. An example of a direct rating method of scoring:

Criteria	OPTION 1		OPTION 2	
	Option Performances	Scores (0÷10)	Option Performances	Scores (0÷10)
Number of jobs created	150 jobs created	7 (good performance)	30 jobs created	4 (poor performance)
Impacts on the ecosystem	Loss of 0.5ha of ancient woodland	5 (acceptable Performance)	No loss of ancient woodland	10 (exceptionally good performance)
Integration with other policy objectives and strategies	The project aligns with economic objectives, but conflicts with environmental and sustainability objectives	2 (negative performance)	The project aligns with local and regional objectives. No significant conflicts	9 (extremely good performance)

Figure 58: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

While highly simple to use and especially useful for qualitative criteria, a direct rating methodology is not as logically sound as other scoring methods. It should be mentioned that the scales used to judge the performance of alternatives are typically Likert-type scales. Unlike interval scales, which have predefined standard units that ensure equal distance between successive values on the same scale, the distance between each value in Likert-type scales is not explicitly defined. Therefore, Likert-type scales have no cardinal value and should preferably only be used to determine the ordinal raking of the possibilities under consideration against the various criteria.

In order to make up for the lack of theoretical rigour and improve the reliability of the results, careful consideration must be given to the selection of the most appropriate scale width to allow for adequate distinction between different performance levels. Wider interval scales are more detailed and hence better capture performance differences between choices, but narrow scales should be utilized only when knowledge about the criteria and potential matching performances is limited.

Example: A comparison of different Likert-type scales typically used for scoring.

<table>
<tr><th colspan="2">Five-Point Scale
(1 ÷ 5)</th><th colspan="2">11-Point Scale
(0 ÷ 10)</th><th colspan="2">Seven-Point Scale
(-3 ÷ +3)</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Very Poor Performance</td><td>0</td><td>Totally Unacceptable Performance</td><td rowspan="2">-3</td><td rowspan="2">Very Poor Performance</td></tr>
<tr><td>1</td><td>Extremely Poor Performance</td></tr>
<tr><td>2</td><td>Very Poor Performance</td><td rowspan="2">-2</td><td rowspan="2">Poor Performance</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">Poor Performance</td><td>3</td><td>Poor Performance</td></tr>
<tr><td>4</td><td>Slightly Poor Performance</td><td>-1</td><td>Slightly Negative Performance</td></tr>
<tr><td>-</td><td>-</td><td>-</td><td>-</td><td>0</td><td>Neither Negative Nor Positive impacts – Neutral Performance</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">Acceptable Performance</td><td>5</td><td>Acceptable Performance</td><td rowspan="2">+1</td><td rowspan="2">Slightly Positive Performance</td></tr>
<tr><td>6</td><td>Fairly Good Performance</td></tr>
<tr><td rowspan="2">4</td><td rowspan="2">Good Performance</td><td>7</td><td>Good Performance</td><td rowspan="2">+2</td><td rowspan="2">Good Performance</td></tr>
<tr><td>8</td><td>Very Good Performance</td></tr>
<tr><td rowspan="2">5</td><td rowspan="2">Very Good Performance</td><td>9</td><td>Extremely Good Performance</td><td rowspan="2">+3</td><td rowspan="2">Very Good Performance</td></tr>
<tr><td>10</td><td>Exceptionally Good Performance</td></tr>
</table>

Figure 59: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Additionally, efforts should be undertaken to develop a consistent set of descriptors for the outcomes and impacts associated with each point on the scale. Once this tabular information for each criterion in the multi-criteria framework has been compiled, analysts and decision makers can utilize it to try to decrease inconsistencies in the scoring systems.

3.3.2 Proportional Scoring Approach

Another simple and quick method for assigning scores is the proportional scoring methodology. It is most appropriate for quantitative criteria and is only applicable in decision-making circumstances involving the evaluation of several possibilities. The first step in this strategy is to choose an appropriate interval scale for comparing the various performance levels of the options against the various criteria (preferably a 0 to 1, or a 0 to 100 interval scale).

For each criterion, the choice with the worst performance receives the lowest score on the scale (i.e. 0), while the option with the best performance receives the highest score (i.e. 1 in the case of a [0-1] scale, or 100 in the case of a [0-100] scale). The remaining alternatives under consideration are given intermediate scores that represent their performance in relation to these two end criteria.

The proportional scoring approach, in particular, assumes that the relationship between criterion performances and performance scores for each criterion can be portrayed as a linear and monotonically increasing (for criteria expressed as a benefit condition) or decreasing (for criteria characterised as a cost condition) function for each criterion. A simple mathematical percentage can thus be used to calculate the scores of an option a with intermediate performance x(a) against a specific criterion(Dean, 2022):

$$x(a) = [Highest\ Score\ on\ the\ Scale] \times \frac{Performance\ of\ Option\ a - Worst\ Performance}{Best\ Performance - Worst\ Performance} \quad (3)$$

The main problem of this approach, as seen below with a practical example of proportional scoring, is its reliance on the set of possibilities. Indeed, as is obvious, changes in the original list of options (e.g., removing the original best and worst options from the list, or including another option with the worst/best performance against a given criterion) are likely to result in variations in the original performance scores.

An example of a proportional scoring method. Three different light bulbs are compared against four criteria:

Criteria	Performances		
	Light Bulb 1	Light Bulb 2	Light Bulb 3
Price	£ 2.82	£ 0.99	£ 4.85
Luminosity	470 Lumens	400 Lumens	1055 Lumens
Consumption	4 Watts	40 Watts	7.5 Watts
Expected Duration	15000 hours	2000 hours	13000 hours

Best Performances

Worst Performances

Criteria	Performances Scores (0 ÷ 1)		
	Light Bulb 1	Light Bulb 2	Light Bulb 3
Price	$\frac{2.82-4.85}{0.99-4.85} \times 1 = 0.53$	1	0
Luminosity	$\frac{470-400}{1055-400} \times 1 = 0.11$	0	1
Consumption	1	0	$\frac{7.5-40}{4-40} \times 1 = 0.90$
Expected Duration	1	0	$\frac{13000-2000}{15000-2000} \times 1 = 0.85$

Figure 60: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

3.3.3 Pairwise Comparison Approach

A third scoring methodology, developed directly from the AHP method (see Section 3.1.2), is based on a series of pairwise comparisons between choices for each criterion. Decisions about the relative merits of each choice are translated into a specified scale (for example, the AHP's nine-point nominal scale). The normalised principal eigenvector (or the normalised geometric means) of the pairwise comparison matrices of the options (one matrix for each decision criterion considered in the analysis) is then calculated to determine the local priority (or score) of each option with reference to each criterion. With this method, scores are assigned on a [0-1] scale.

Subsequently, as previously stated, this is not an interval scale, but is (questionably) understood as a normalised ratio scale (Saaty, 1990b and 1993). When there are many alternatives and criteria to compare, the pairwise comparison strategy can become time consuming (with N criteria and M options, N(M(M-1)/2) pairwise comparisons must be performed). Similarly to the proportional scoring strategy, scores in this approach appear to be dependent on the set of options, thus if additional alternatives are introduced into the study, new pairwise comparisons must be done. Example of a pairwise comparison approach to scoring with three criteria and three options:

Criterion C_1	a_1	a_2	a_3
a_1	1	1/3	5
a_2	3	1	9
a_3	1/5	1/9	1

Criterion C_2	a_1	a_2	a_3
a_1	1	4	1
a_2	1/4	1	7
a_3	1	1/7	1

Criterion C_3	a_1	a_2	a_3
a_1	1	4	9
a_2	1/4	1	8
a_3	1/9	1/8	1

⇩

Retrieved Performance Scores against C_1	
a_1	0.11
a_2	0.81
a_3	0.08

Retrieved Performance Scores against C_2	
a_1	0.48
a_2	0.36
a_3	0.16

Retrieved Performance Scores against C_3	
a_1	0.69
a_2	0.26
a_3	0.05

Figure 61: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

3.3.4 Value Function Approach

Finally, a particularly rigorous scoring strategy incorporates the employment of a value function to translate the impacts of the options against a specific criterion into the chosen measurement scale. Belton and Stewart (2002) provide a full description of this approach, which incorporates the following main steps in basic terms:

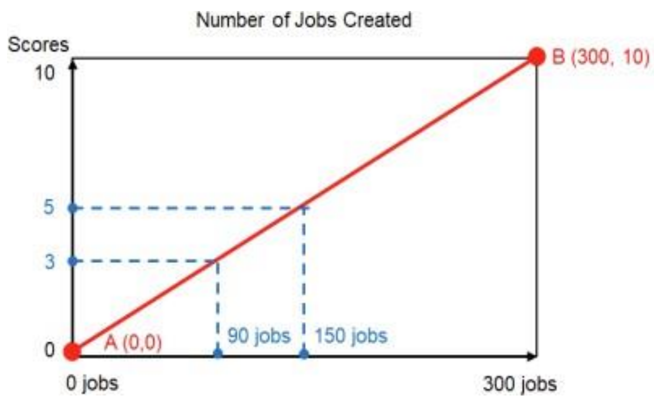
- Choosing the best interval scale for measuring performance against the various criteria (e.g., a 0 to 1 interval scale).
- For each criterion, define the general characteristics of the value function that will be used to measure the various options' performances (e.g., linear or non-linear function; monotonic or non-monotonic function). The value function's shape should represent the decision-makers' values and preferences.
- Identifying a few crucial levels of performance for the criterion under consideration (e.g., the best and worst potential performances against that criterion). These key performance thresholds will be unambiguously linked to specific measuring scale scores.

- Build the value function so that it satisfies all of the key properties of the function's general form and goes through all of the previously determined critical locations.

- Using the value function that was created to determine the scores of each choice against the provided criterion (graphically or mathematically).

The preceding steps are described in greater detail below. In this example, a 0 to 10 scale was used to compare the performance scores of the various solutions to the criterion of number of new jobs produced. To unambiguously correlate each performance value with a distinct performance score on the selected interval scale, a linear and monotonically increasing function was used. This straightforward value function can be defined by defining only two points (corresponding to two important levels of performance) that the function must pass through.

The chosen points represent the best and worst potential levels of performance against the criterion under consideration, which in this case are assumed to correspond to no employment being generated and 300 new jobs being provided. As a result, a score of 0 represents the lowest conceivable performance, whilst a score of 10 represents the finest possible performance. The value functions so generated allow translation from the natural scale of impact measurement (i.e. number of jobs created) to the 0 to 10 scale and may be used to determine the relative performance of all options at hand against this criterion very rigorously. An example of a value function scoring approach:



Equation of a Line from 2 Points: $\frac{X - X_A}{X_B - X_A} = \frac{Y - Y_A}{Y_B - Y_A}$

With A = (0,0) and B (300,100) → $Y = \frac{1}{30}X$

X (Number of Jobs)	Y (Scores)
0	0
90	3
150	5
300	10

Figure 62: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

In contrast, the slope of the value function has the direction represented above for linear and monotonic functions, and criteria characterised as a benefit condition (where the highest value against the criterion is the most preferred), the slope of the value function is reversed for criteria characterised as a cost condition (where, vice versa, the lowest value is the most preferred). Although incredibly useful, a linear and monotonic value function cannot always be used to assess performance.

It is not always good to aim to create as many jobs as possible in a given location because this may result in unequal economic development between regions. In such cases, a piecewise-defined function can be used, and an intermediate point is defined to indicate the critical level of achievement above which further job opportunities in an area are not highly valued, as this may drain the surrounding regions of workforce, investments, and other resources. Other decision-making circumstances may also necessitate the identification of non-linear functions, which are far more difficult to draw.

Von Winterfeldt and Edwards (1986), Watson and Buede (1987), Belton and Stewart (2002), and Barfod and Leleur (2014) offer methods for calculating such value functions.

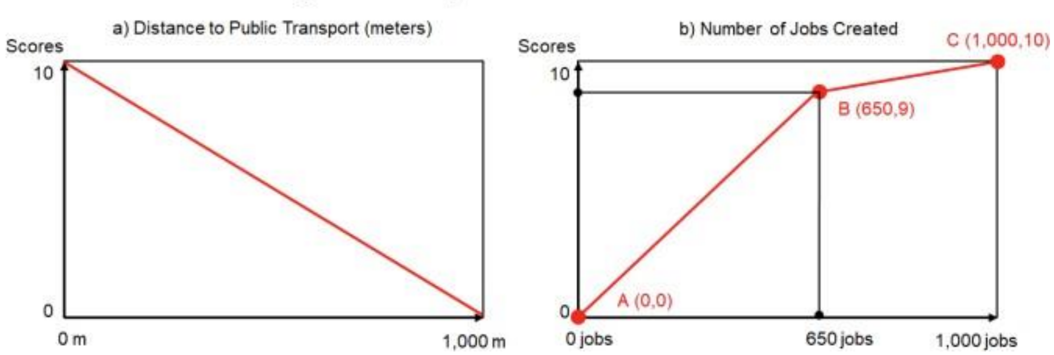


Figure 63: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

3.3.5 Use of Threshold Values

Compensatory decision models are represented by full aggregation MCA approaches such as MAUT, AHP, and the simple weighted additive model. Indeed, with such methodologies, bad performance against some criteria can be offset by good performance against others, allowing an option's overall performance score to stay high. As a result, while such approaches are simple, they carry the danger that a choice that performs poorly on numerous criteria may nevertheless be chosen as the best solution to the problem at hand.

This circumstance is well illustrated in the appraisal summary table below. According to the weighted summation rule, option 2 appears to be superior to option 1 in this table. However, the former alternative fails to meet two of the four conditions. Despite being placed second, option 1 has a more balanced and robust performance profile than option 2. Such circumstances are likely to raise questions and debates about the analysis's result. Difficulties selecting the optimal option using full-aggregation MCA approaches, for example.

Table 16: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Objectives/ Criteria	Weights (0÷100)	Option 1		Option 2	
		Scores (0÷10)	Weighted scores	Scores (0÷10)	Weighted scores
C1	25%	7	1.75	3	0.75
C2	25%	5	1.25	9	2.25
C3	25%	5	1.25	4	1
C4	25%	7	1.75	9	2.25
Total	**100**		**6.0**		**6.25**
Preference Rank		**2**		**1**	

To mitigate these kinds of problems, particular threshold values might be assigned to at least the most critical criterion. Such threshold values constrain an option's worst acceptable performance against those specific criteria, so that if it exceeds such values, it is automatically rejected, regardless of its overall performance score or performance against the remaining criteria (Nijkamp and Ouwersloot, 1997; Nijkamp and Vreeker, 1999). The application of threshold values so implicitly elevates the importance of those criteria for which thresholds have been established (Benoit and Rousseaux 2003).

Threshold values can be established in accordance with policy objectives and legal instruments, scientific criteria identifying boundaries to natural processes and systems, or ethical norms (Rosemberg, 2001). The type of threshold to be applied to a given criterion is also determined by how the criterion is specified.

The thresholds indicate the value below which the performances of the options become unacceptable for criteria described as a benefit condition (where the highest value against the criterion earns the highest marks). The thresholds indicate the value over which the impacts of the options may imply excessively large societal costs for criteria described as a cost condition (for which a lower value is preferred).

For situations with significant uncertainties, it may be more useful to define a threshold value as an interval, with the extreme values indicating a more prudential and a more liberal estimate of the acceptable threshold (Mendoza et al., 2002). The graph below depicts the relationship between option performance and the criterion of loss of ancient woodland, as well as threshold values. In this example, two threshold values have been defined: 35 hectares and 20 hectares.

If the performance of the option under consideration (for example, an infrastructure program in a rural area of a country) exceeds 35 hectares (i.e., the program is expected to destroy more than 35 hectares of ancient woodland), the option receives a low score and a'red flag,' indicating that this option is not acceptable regardless of its performance against the other criteria. If the option's performance is less than 20 hectares, it earns a relatively high score and a "green flag," indicating that there is no cause for alarm. Finally, if the option's performance ranges between 20 and 35 hectares, the option can still be adopted, subject to more investigations, studies, and debates.

Example: An example of how to use threshold values

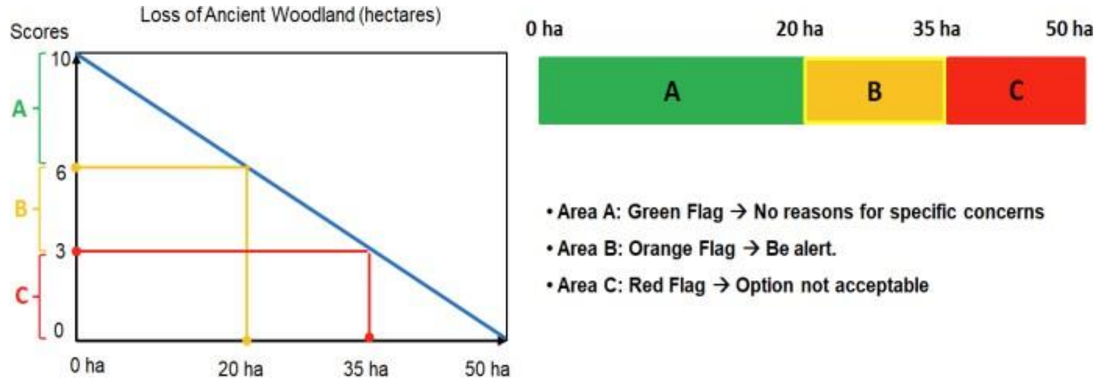


Figure 64: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

3.4 Weighting

Given the significant value judgements involved in this step and the strong influence that this parameter can have on the results of the analysis, minor changes in the set of weights can easily result in different option rankings, assigning weights to the objectives and associated criteria is a critical and contentious stage of any MCA exercise. The practical impossibility of calculating objective weights has limited the application of MCA outside academic settings in numerous nations throughout time (e.g., Annema et al., 2015; Quinet, 2000). As a result, weights are frequently referred to as MCA's 'Achilles' heel' (BTE, 1999). An analysis of the relevant literature on the application of MCA in planning and policy reveals the existence of two opposing schools of thought regarding the appropriate technique to calculate weights:

1. Weights could be generated (directly or indirectly) from previous decisions on situations similar to the decision-making situation under consideration, according to Nijkamp and colleagues (1990).
2. According to Van Pelt (1993), weights could be utilized in the endeavor to differentiate and achieve a balance between short-term and long-term objectives.
3. According to Munda (2004 and 2008), weights should reflect some ethical principles (e.g., a 'ecological stability' position, implying higher weights for criteria related to environmental dimension; a 'economic prosperity' position, implying a strong consideration for economic criteria; a'social equity' position, implying the assignment of higher weights to social objectives), and different weighting schemes should thus be used to examine their consequences on the finite finite finite finite finite finite
4. The Australian Resource Assessment Commission encourages adjusting and testing multiple sets of weights as part of an interactive process between analysts and decision-makers in its MCA recommendations (RAC, 1992).
5. Weights, according to Dimitriou and colleagues (2010) and Brown and colleagues (2001), should be determined from policy documents and government directives.
6. Dodgson and colleagues (2009) advise the team of analysts conducting the analysis to act out the roles of the various problem stakeholders in order to ensure that the chosen weighting scheme reflects the interests of all the various parties and groups involved or affected by the given decision-making situation.

7. Stirling and Mayer (2001), Proctor and Drechsler (2006), and Macharis and Bernardini (2015) go even farther, arguing that weights should be extracted directly from problem stakeholders as part of a participatory MCA exercise.

However, none of the weighting systems proposed thus far appear to be capable of breaking the impasse. While ensuring consistency with earlier selections is crucial, the first of the following options may be troublesome since complete information on previous choices may not be available. Previous decisions may not have been the best resolutions(Dean,2022).

While almost everyone recognizes the importance of distinguishing between the impacts produced by a policy or project in the short term and those produced by this policy or project in the long term, there is little agreement on the priority level to assign to these two categories of impacts. For example, the long-running debate over 54 discounting procedures in CBA (Ponti, 2003; El-Haram and Horner, 2008; Koopmans and Rietveld, 2013) and, more broadly, the multiple divergent viewpoints on the topic of sustainable development and intergenerational equity (for an overview of this topic, see Van Pelt, 1993 and Munda, 1995) demonstrate this clearly.

When weights are selected by analysts or decision-makers, they invariably turn out to be mainly arbitrary. As a result, they will tend to differ depending on the will of the person (people) in command of the process. This may result in inconsistencies in choices, with some projects being accepted based on a specific weighting system and other projects that are quite identical being refused due to the application of alternative weights. Even the use of alternative weighting schemes, while important for testing the robustness of the analysis, cannot overcome the subjectivity problem because, ultimately, a definitive weighting scheme leading to a final option ranking must be chosen.

Although the idea of having an appraisal and evaluation process driven by policies may be intriguing to some, it should be highlighted that objectives and strategies are established at an overly broad level in policy documents. This means that particular information on decision criteria and weights cannot be drawn unequivocally from such texts and are highly likely to be subject to multiple interpretations by politicians, specialists, and the general public. However, even if weights can be found in policy documents and official instructions, significant issues remain. Indeed, such policy weights are likely to shift from year to year, depending on the makeup of legislatures, political trends, and the needs of bureaucrats. As a result, one might expect more wrangling over the weights to be adopted, as well as the risk that special-interest groups will be given disproportionate influence in the decision-making process.

Finally, eliciting weights from stakeholder groups with competing agendas will invariably result in conflicting weighting schemes, and any attempt to reconcile these differences (via negotiation or, more simply, by calculating the average of a wide range of values) will almost certainly result in process deadlocks (Dean, 2018 and 2021).

To prevent (or at least lessen) subjectivity and disputes, some MCA methods and procedures forgo using criterion weights in the analysis, implicitly allocating equal weight to all criteria. However, this approach has been heavily criticized, with some authors (e.g., Sayers et al., 2003; Dimitriou et al., 2010; Gan et al., 2017) claiming that the lack of any guidance on which dimension and objective matter is most likely to reduce transparency and produce inconsistent decisions.

Furthermore, Munda (2008) emphasizes that assigning the same weight to all criteria does not necessarily guarantee that all of the different dimensions considered in the analysis (e.g., economic, environmental, and social dimensions) have the same importance because any dimension will ultimately be weighted based on the number of criteria it contains. Each dimension should have the same number of criteria in order to be given the same weight. However, in order to achieve this constraint, analysts may be tempted to remove some critical criteria and objectives from the value-tree and/or add some new criteria, even if they are utterly irrelevant or redundant.

3.4.1 Weighting Techniques

A wide range of practical weighting techniques have also been developed to aid in the ascription of weights, despite the fact that, as highlighted by several authors (e.g. Hokkanen and Salminen 1997; Rogers et al., 2000; Clemen and Reilly, 2013; Zardari et al. 2015), some of these methods lack a proper theoretical foundation. These techniques differ in terms of procedures, accuracy, degree of complexity, and ease of use, and thus, when applied to the same set of criteria, typically result in different weighting schemes (Hobbs, 1980; Schoemaker and Waid, 1982; Poyhonen and Hamalainen, 2001; Zardari et al. 2015).

Most crucially, the various weighing systems are founded on various assumptions about the real meaning and purpose of weights. In this regard, weighing strategies can be neatly grouped into two major categories, reflecting one of the core differentiating characteristics of MCA methods: compensatory and non-compensatory (Diakoulaki and Grafakos, 2004).

- **Compensatory weighting approaches** are important for generating weights as trade-off coefficients in MAUT and other full aggregation methods that give full compensation between criteria (see Section 3.1.2). These trade-offs suggest the possibility of compensating for a disadvantage on one criterion with a sufficiently big advantage on another. Weights, in this context, represent how much of one criterion analysts and decision-makers are ready to give up in order to boost performance on another criterion by one unit (Munda, 2008; Bouyssou et al., 2000; Belton and Stewart, 2002).
- **Non- compensatory weighing strategies,** such as those recommended for outranking and other noncompensatory MCA methods like ELECTRE and PROMETHEE (see Section 3.1.3), are especially useful for constructing weights as significance coefficients. An significance coefficient expresses the relative relevance of one criterion to the others (Munda, 2008; Bouyssou et al., 2000; Belton and Stewart, 2002).

To better understand this distinction, consider an example in which different project possibilities are evaluated based on two key criteria: investment costs and loss of ancient woods. Assume that the weight of the former criterion is twice that of the latter. If these two weights are stated as trade-off coefficients in the context of, say, an MCA based on a weighted additive model, it indicates that the decision-maker values 1 unit on the investment cost criterion as much as 2 units on the loss of ancient woodland criterion.

If the two weights are interpreted as importance coefficients to be used with 56 non-compensatory MCA methods, the weights of criteria should be interpreted as an indication that the decision-maker considers investment costs to be twice as important as the loss of ancient woodland. In the first case, when determining weights, the relevant question to ask is ‘how much would you be willing to increase construction costs to preserve a unit of ancient woodland?’, whereas in the second case the question becomes ‘what is more important: investment costs (i.e. economy) or loss of ancient woodland (i.e. environment)’. This example demonstrates how trade-off weights describe a quantifiable relationship between performance scores and are related to the alternatives' performance levels versus the criterion in question.

Importance coefficients, on the other hand, are simply determined by the meaning and significance of the criteria themselves (i.e., the more important the criterion is, the more weight it receives) and are unrelated to either the specific measurement scale used to assess performance scores against the criteria or the possible ranges of performance levels against the criteria (Beinat, 1997; Munda, 2008).

It is critical to establish consistency between how weights are calculated and how they are used in the aggregation model. For example, it is incorrect to elicit criteria as significance coefficients and use them in a model based on a linear weighted aggregation method, which implies trade-offs between criteria. Unfortunately, the meaning of criterion weights and their implications is often misinterpreted or ignored in the MCA literature, resulting in inconsistency in many MCA applications. In fact, it appears that researchers, analysts, and decision-makers choose weighting techniques based solely on their appeal and ease of use (e.g. Yoe, 2002; Macharis et al., 2012; Barfod et al., 2018; Salling et al., 2018; Németh et al., 2019), attach weights to criteria based on their relative importance, and then combine them with performance scores using a simple weighted additive model (e.g. Ananda and Herath, 2003; Freudenberg, 2003; EC, 2008 and 2014; Blades, 2013; van Ierland et al., 2013; Barquet, 2016).

The most frequent compensatory and non-compensatory weighting systems are briefly given in the following sections. For a more detailed examination of these techniques and descriptions of other weighting approaches, see Nijkamp and colleagues (1990), Beinat (1997), Hajkowicz and colleagues (2000), Rogers and colleagues (2000), Diakoulaki and Grafakos (2004), Bouyssou and colleagues (2006), Rogers and Duffy (2012), Zardari and colleagues (2015), and Odu (2019).

3.4.2 Compensatory Weighting Techniques

As mentioned earlier, compensatory weighting approaches are specifically created for compensatory MCA methods (e.g., MAUT methods and simple additive weighting models). Weights are employed in such systems to regulate the marginal contribution of each criterion to the total performance score (or overall utility) of each choice. They thus take on the meaning of trade-off coefficients and turn out to be dependent on measurement scales and criterion performance level ranges. Compensatory weighing strategies compel analysts and decision-makers to describe trade-offs between criteria in order to indicate how much they are willing to sacrifice in one area in order to improve another. There are no considerations for the importance of the criteria in such systems, which imply lengthy and rather intricate procedures.

Trade-Off Weighting Technique

This is likely the only technique proposed in the literature in which weights may be derived as trade-off coefficients with no ambiguity about their actual meaning. This method is based on a pairwise analysis of criteria and was created by Keeny and Raiffa (1976) as part of their work on MAUT and the weighted additive form of the multi-attribute utility function.

Two hypothetical options a1 and a2 are generated given N criteria for which weights must be computed. The performance profiles of the two choices are considered to differ solely in two criteria, cK, which can be used as a reference criterion, and cR.

Option a1 is supposed to have the best performance against cK and the lowest performance against cR. Option a2 is expected to have the worst possible performance against cK. Analysts and decision-makers must then alter the performance score of option a2 on cR so that the overall utilities (or global performance scores) of the two options are equal.

As an outcome, this choice reflects the trade-off between cK and cR. The problem can be represented in symbols using the equations xK(a1), xR(a1), xK(a2), and xR(a2) to indicate the performances of the two options against cK and cR, and wK and wR to indicate the weights of the two criteria:

$$U(a_1) = U(a_2)$$

$$U(a_1) = \sum_{j=1}^{N} w_j \times x_j(a_1) = \sum_{j=1}^{N} w_j \times x_j(a_2) = U(a_2)$$

$$\sum_{\substack{j=1 \\ j\neq K,R}}^{N} w_j \times x_j(a_1) + w_K \times x_K(a_1) + w_R \times x_R(a_1) = \sum_{\substack{j=1 \\ j\neq K,R}}^{N} w_j \times x_j(a_2) + w_K \times x_K(a_2) + w_R \times x_R(a_2)$$

$$\text{Since} \quad \sum_{\substack{j=1 \\ j\neq K,R}}^{N} w_j \times x_j(a_1) \sim \sum_{\substack{j=1 \\ j\neq K,R}}^{N} w_j \times x_j(a_2)$$

$$\text{Then} \quad w_K \times x_K(a_1) + w_R \times x_R(a_1) = w_K \times x_K(a_2) + w_R \times x_R(a_2)$$

$$w_K\,[x_K(a_1) - x_K(a_2)] = w_R\,[x_R(a_2) - x_R(a_1)]$$

$$\frac{w_K}{w_R} = \frac{[x_R(a_2) - x_R(a_1)]}{[x_K(a_1) - x_K(a_2)]}$$

Figure 65: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

The aforementioned trade-off connection between the two criteria cK and cR becomes an equation with two unknown variables, wK and wR, with the performances xK(a1), xR(a1), and xK(a2) set at the outset and xR(a2) opportunely modified to make the two options indifferent.

Analogous equations in two unknown variables (i.e. the weights of the two criteria examined in each equation) can be discovered by repeating the same approach for all the pairwise combinations of criterion cK with regard to the remaining N-2 criteria. To establish the value of the N weights, a system of N equations must be solved. This system includes the N-1 equations that explain the trade-off relationships between pairs of criteria, as well as the normalization requirement that requires the sum of weights to be equal to 1.

SWING Weighting Technique

The trade-off weighting strategy, while theoretically reasonable, can be mentally demanding. The Swing technique (von Winterfeldt and Edwards, 1986) represents a simpler and more controllable approach to finding weights as trade-off coefficients. This technique starts with the development of a benchmark option that performs the poorest against all of the N choice criteria examined in the multi-criteria decision-making problem at hand.

Beginning with the worst-case scenario, various hypothetical possibilities are chosen by increasing (or'swinging') one criterion at a time, from the worst to the best possible performance. Overall, as many hypothetical choices as the number of decision criteria included in the multi-criteria framework will be generated. Analysts and decision-makers are then asked to rank all of these hypothetical choices (each of which is connected with a swing of a specific criterion from the worst to the best outcome) depending on which swing would result in the greatest, second largest, and so on improvement.

The choice with the most convenient swing (and the accompanying criterion) is then awarded 100 points. All additional swings implied by each of the other selections (and associated criteria) are expressed as a percentage of the most preferred swing.

Equal weights

- When there are no statistical or empirical grounds for choosing a different scheme, all variables in many composite indicators are assigned the same weight. When it comes to policy assessments, equal weighting could indicate recognizing an equal status for all indicators. Alternatively, it could be due to a lack of understanding of causal links, ignorance about the appropriate model to use, or even a lack of consensus on alternative solutions. The influence of equal weighting on the composite indicator is also affected by whether equal weights are applied to single indicators or components (which group a variety of indicators).
- When using equal weighting, it is possible to include an element of double counting into the index by mixing indicators that are highly correlated. Testing indicators for statistical correlation (e.g. Pearson correlation coefficient) and selecting only indicators with a low degree of correlation or modifying weights accordingly, e.g. giving less weight to correlated indicators, has frequently been proposed as a solution. Additionally, reducing the number of indicators in the index may be advantageous for reasons such as transparency and parsimony.
- Almost invariably, there will be some positive correlation between distinct measurements of the same aggregate. As a result, a rule of thumb should be utilized to determine the level beyond which correlation results in duplicate counting. If weights should ideally reflect each indication's contribution to the index, double counting should be discovered not just by statistical analysis but also by a comparison of the indicator to the other indicators and the phenomenon they all intend to assess.

3.4.3 Non-Compensatory Weighting Techniques

For non-compensatory MCA approaches (e.g., ELECTRE and PROMETHEE), where weights serve as significance coefficients, non-compensatory weighting procedures should be utilized. Because of the aggregation restrictions imposed by these methods, weights reflect the relevance of the criteria themselves and are independent of measurement scales and performance level ranges. A number of non-compensatory weighting strategies have been developed over time.

Since several of these strategies appear to be small variations on one another, it has been demonstrated that they can result in drastically different weighting schemes (Doyle et al., 1997; Bottomley et al., 2000; Hajkowicz et al., 2000). Non-compensatory weighting strategies are more intuitive and easier to apply than compensatory weighting techniques. As a result, they are widely used as part of compensating MCA approaches, despite the fact that, as previously stated, this is likely to produce in incorrect and inconsistent results.

Simple Rating

The Simple Rating is one of the most basic ways for determining criteria weights based on the relative importance of the criteria. To show the significance of each criterion, a numerical score on a specific scale (e.g. 1-5 or 1-10), often paired with a qualitative opinion on a Likert scale (e.g. extremely important; significant; of some importance; unimportant), is employed. The weights can then be normalised to the [0-1] interval (or to 100%) by dividing each weight by the sum of all weights.

An example of a Likert-type scale that could be used for weighting procedures:

Level of Importance	Weights
Extremely Important	5
Very Important	4
Important	3
Moderately Important	2
Slightly Important	1

Figure 66: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Graphical Weighting

The use of this method allows analysts and decision-makers to convey their preferences entirely visually. To begin, a horizontal line depicting the scale on which judgments are made is drawn. A mark is then placed anywhere along this line to reflect the importance of each criterion. The importance of the criteria grows when the mark is moved closer to the right end of the line. The distance from the mark to the left end of the line is then measured to calculate a quantitative value for each criterion. This amount is then multiplied by the total length of the line.

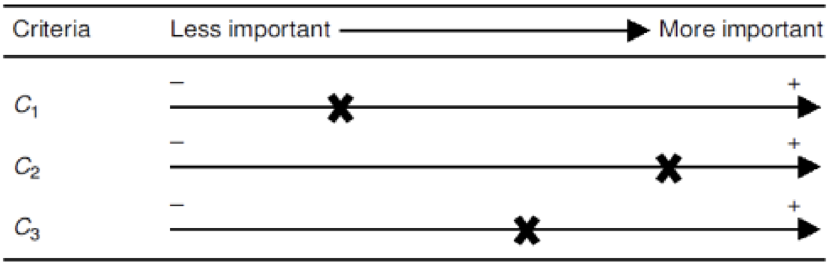


Figure 67: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Ranking System

The Ranking System is founded on the premise that weight elicitation is a difficult and time-consuming task. It is rare to find numerically precise information on the weights of criterion. However, most of the time, ranking the criteria in order of priority is doable. The criteria are thus sorted from most important to least important using this technique, and each criterion is then allocated a value based on its position in the rank. Given N criteria, the first ranked criterion is assigned a value of 1; the second ranked criterion is allocated a value of 2; and so on until the least significant criterion is assigned a value of N. If many criteria are deemed to be of equal importance, an average value is applied to them. Following the assignment of all values, the normalised significance weights of criteria wj are determined using the formula:

$$w_j = \frac{N - r_j + 1}{\sum_{j=1}^{N}(N - r_j + 1)}$$

Where:

rj is the ranking value for the j-th criterion.

N is the total number of criteria.

The Table below includes an illustrative example of the ranking system approach to weighting

Illustrative example of the Ranking system to ascribe criterion weights:

Criteria	Rank Position	Correspondent Rank Value	N - r_j + 1	w_j
C_1	1st	1	6	0.286
C_2	6th	6	1	0.048
C_3	4th	4	3	0.143
C_4	2nd/3rd (same position as C_5)	(2+3)/2 = 2.5	4.5	0.214
C_5	2nd/3rd (same position as C_4)	(2+3)/2 = 2.5	4.5	0.214
C_6	5th	5	2	0.095
		∑ =	21	1

Figure 68: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Ratio System

This method is quite similar to the ranking system described above. The weighting procedure begins by ranking the criteria from most important to least important. A value of one is assigned to the least important criterion. All of the other criteria are then compared to this one and given a value larger than one to show their relevance in comparison to the least significant criterion. The weights wj can then be normalized using the following equation:

$$w_j = \frac{r_j}{\sum_{j=1}^{N} r_j)}$$

Where: rj is the ranking value for the j-th criterion; and N is the total number of criteria .

The SMART method uses a similar approach to weighing (Edwards, 1977). With this method, the least significant criterion is given 10 points, while the other criteria are given additional points to account for their position in the rank order. The raw weights obtained are then normalized by dividing each weight by the total number of points assigned.

Point Allocation

A specific number of points (usually 10 or 100 points) must be allocated among the defined criteria using this technique. The more points a criterion earns, the more important it is. Unlike the simple rating technique, which allows analysts and decision-makers to change the importance of one criterion without changing the weight of the other criteria, this approach only allows you to give a criterion more points by subtracting some points from other criteria. Although not considered a compensatory weighting strategy (weights are assigned based on the relevance of criteria in this approach), the point allocation technique challenges analysts and decision-makers to make trade-offs when assigning criteria.

Example of application of the Point Allocation method

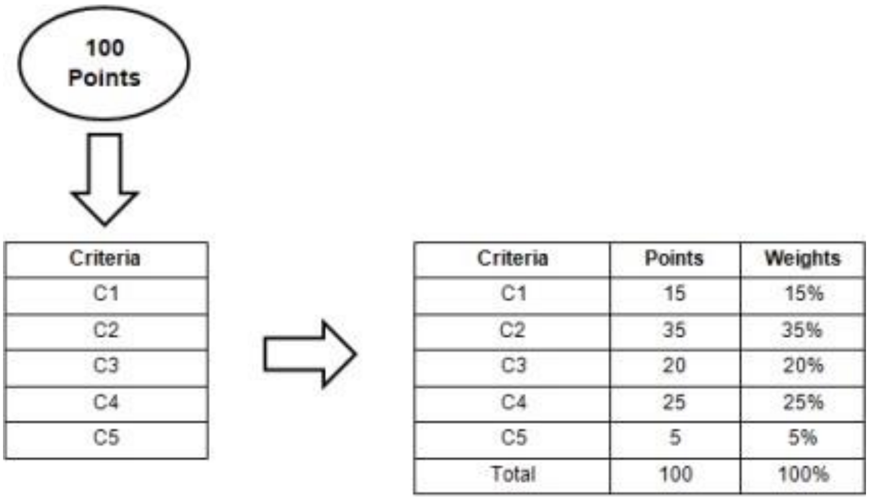


Figure 69: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

While intuitive, this strategy becomes increasingly challenging as the number of criteria in the value tree grows. When there are many criteria, it may be more convenient to first divide the fixed number of points among the selected overarching dimensions of criteria (e.g., economic, environmental, and social) and then distribute the allocated amounts of points among the various criteria included within each dimension.

Example of using the Point Allocation method with many criteria:

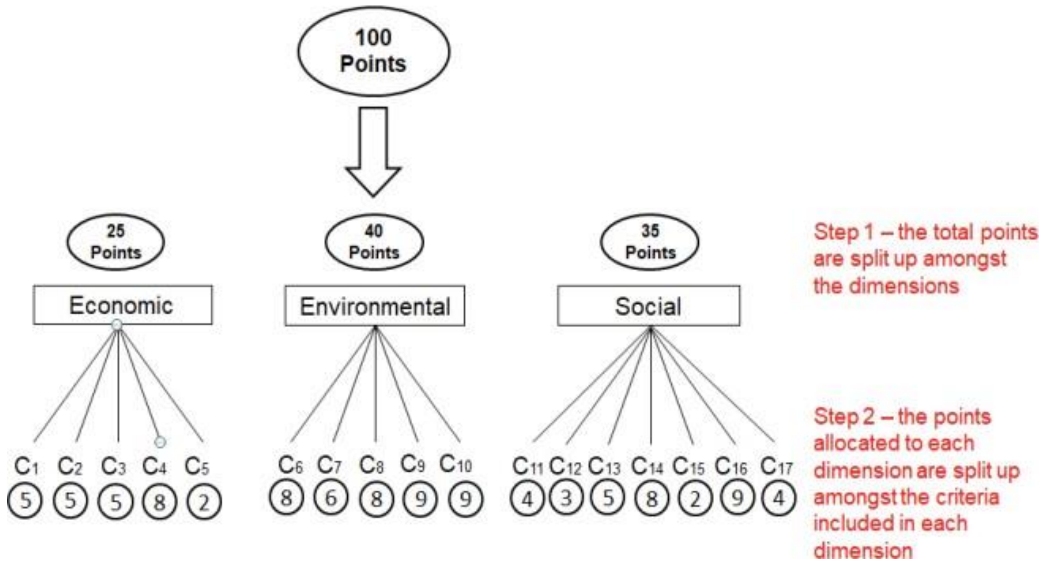


Figure 70: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Paired Comparison

This strategy includes comparing each criterion in pairs to every other criterion. As shown in Section 3.1.2, a popular form of paired comparison to determine criteria weights is derived from the AHP and requires comparing criteria in pairs using a nine-point scale to express their relative importance (from 1, when the two criteria are judged to be of equal importance, to 9, when one criterion is judged to be absolutely more important than the other). Normalised weights are produced for all criteria after all paired comparisons have been completed. A simple paired comparison method that does not involve the calculation of the geometric mean or the normalised principal eigenvector of the pairwise comparison matrices (as required by the AHP method).

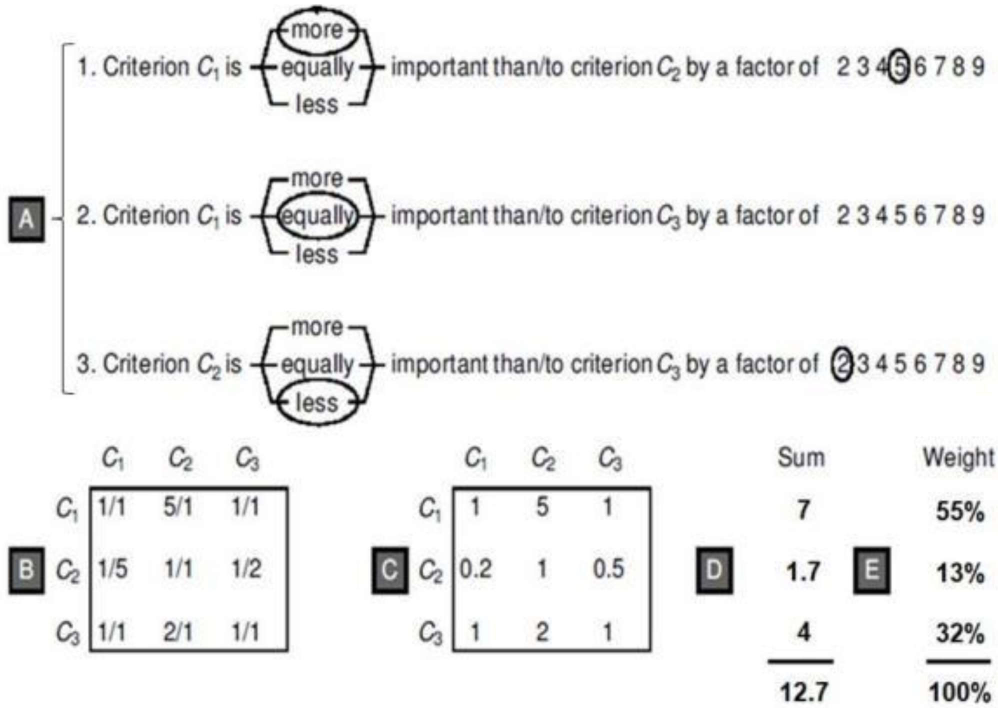


Figure 71: Source: Dean, M. (2022). A Practical Guide to Multi-Criteria Analysis. In Technical Report. https://doi.org/10.13140/RG.2.2.15007.02722

Once the weights and scores have been assigned, they can be combined according to the aggregation rules imposed by the MCA method used to handle the specific situation at hand.

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