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A study of the evolution of the city's public policies from the perspective of the mobility of residents in priority neighbourhoods

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Abstract

Mobility inequalities in French priority neighbourhoods, or *Quartiers Prioritaires de la Politique de la Ville* (QPVs), have historically been addressed through transport infrastructure and urban regeneration policies. However, these approaches do not explain the mobility difficulties experienced by residents, which also stem from social, economic and educational inequalities. This paper examines how French public policies addressing mobility in priority neighbourhoods have evolved from an infrastructure-centred approach towards a broader conception of inclusive mobility. It asks to what extent this shift reflects a transformation in the understanding of mobility inequalities. The article combines a historical and policy analysis of urban and transport legislation with a review of academic literature and institutional reports (INSEE, CEREMA, ANRU, ANCT, SYTRAL). It also includes a thematic analysis of French press coverage of priority neighbourhoods using *Europresse* to identify changes in public debate over time. The analysis shows that mobility remained largely secondary within successive urban policies, which primarily focused on housing renewal, social mix and urban regeneration. Since the 2000s, and particularly following the 2019 Mobility Orientation Act (LOM), public action has progressively incorporated the notion of inclusive mobility through personalised support measures such as mobility advice, social driving schools, cycling schools and community-based initiatives. These innovations recognise that access to transport alone is insufficient without developing residents' mobility capabilities. The paper argues that mobility policies are gradually shifting from an infrastructure-based model towards a capability-oriented approach, although investment in personalised mobility support remains marginal compared with expenditure on transport infrastructure.

Keywords

Inclusive mobility; Urban policy; Priority neighbourhoods; Mobility inequalities; France

1. Introduction

Mobility challenges in priority neighbourhoods cannot be explained solely by a lack of infrastructure; they also stem from social inequalities and the unequal distribution of resources, whilst public policies have long favoured a territorial and infrastructure-based approach. The paper will therefore ask the following question: How have public policies addressed mobility in priority neighbourhoods, and to what extent is the emergence of inclusive mobility transforming this approach?



2. Data and methods

This research adopts a qualitative approach, combining historical, policy, and documentary analyses to examine the evolution of French public policies addressing mobility in priority neighbourhoods (QPV). First, a historical analysis was conducted to reconstruct the evolution of French urban policy from the emergence of large housing estates after the Second World War to the introduction of priority neighbourhoods under the 2014 Lamy Act. This historical perspective enables understanding how mobility issues progressively emerged within broader urban regeneration policies.

To complement the institutional perspective, the study includes a thematic analysis of French press articles retrieved through the Europresse database. Articles relating to priority neighbourhoods were classified by dominant themes (housing, employment, security, and mobility) to examine how public debate evolved over time and whether media attention reflected shifts in public policy priorities.

Although this study is primarily based on documentary and policy analysis, illustrative examples from the Lyon metropolitan area are used to show how national mobility policies are implemented at the local level. The objective is not to evaluate the effectiveness of these initiatives empirically but to illustrate the practical translation of national policy orientations into local mobility measures.

Finally, the documentary analysis was complemented by a review of the academic literature on mobility inequalities, urban policy and inclusive mobility. The theoretical framework is mainly based on the concepts of motility (Kaufmann et al., 2004), mobility capital (Joxe, 2022) and the transition from transport planning to sustainable mobility management (Debizet, 2004). These concepts provide the analytical framework for interpreting the evolution of French mobility policies.

3. Results and discussion

3.1 Priority neighbourhoods: an overview of a fantasised urban space at the heart of urban policy

The history of working-class neighbourhoods began after the Second World War with the construction of large housing estates during the *Trente Glorieuses* (1945–75). Faced with a housing shortage in the wake of the war's devastation, growing demand for labour from industry, rural depopulation and an influx of migrant workers, the State responded rapidly by creating entire neighbourhoods on a massive scale. These housing estates (*grands ensembles*) were initially conceived as modern urban projects intended to provide decent housing close to employment opportunities. The example of Vaulx-en-Verin illustrates the scale of development relative to what existed at the time: 40,000 new residents were expected to join the approximately 21,000 recorded in 1968 (Lévêque, 2019). These neighbourhoods were subsequently populated by French and immigrant working-class people, civil servants, young households and returnees from Algeria (Lévêque, 2019), maintaining a high degree of social diversity within the new housing estates. However, this was criticised by Chamboredon and Lemaire (1970).

However, as living standards in France improved and private car ownership became more widespread, the detached house model gained ground shortly after the construction of the *grands ensembles*. – largely because the rise of the car made it possible to live farther from their workplaces. The middle classes living in these estates, who had access to mortgages due to their more stable financial situation than others, moved out of housing estates, leaving the more financially vulnerable part of the population behind. This process progressively concentrated poverty within these estates and transformed what had been presented as symbols of modernity into neighbourhoods increasingly associated with social exclusion.

Whilst the *grands ensembles* were seen as utopian at the time of their construction – offering access to amenities such as heating, lifts and bathrooms, as well as proximity to employment – they were fairly quickly criticised by the late 1960s for their failure in terms of socialisation, housing and the Act of living. Following a period of strong growth, several events were expected to impact these neighbourhoods significantly. In 1973, the first oil crisis hit, and in 1974, Valéry Giscard d'Estaing suspended labour immigration and opened family reunification to immigrants



already in France. French society then experienced a sharp slowdown in growth, placing the working-class population, amongst whom immigrants were particularly prominent, in a highly precarious position. With deindustrialisation, unemployment soared, rising from full employment in the 1960s to mass unemployment (5.6 per cent in 1980 and 9.1 per cent in 1985) severely affecting the working class.

The 1980s saw the onset of urban riots, notably in the Lyon housing estate Les Minguettes, and brought the issues of the suburbs and discrimination to the fore with the March for Equality and Against Racism. This represented the beginning of urban policy aimed at addressing the negative effects of concentrated poverty. The introduction of the 'Social Development of Neighbourhoods' (*Développement Social des Quartiers*, DSQ) programme marked a shift in scale in French public policy, with an ambition that already extended beyond individual neighbourhoods. This first generation of programmes laid the foundations for subsequent urban policies, which progressively expanded their objectives beyond urban renewal. These events marked the emergence of French urban policy, initially focusing on combating territorial inequalities through neighbourhood-based interventions. Working-class neighbourhoods did not become areas of concentrated immigration and poverty through a single mechanism, but through the accumulation of constraints limiting residential mobility and public policy measures that encouraged this demographic pattern. This concentration is thus part of a broader history of inequalities in access to housing, employment and urban resources.

The analysis of the current population must be assessed from several angles. Firstly, it is important to assess the population's social characteristics and compare them with those of the rest of France. It can then be seen that the population in working-class neighbourhoods is younger (average age: 35 years compared with 41 years in the rest of urban areas) and has a higher unemployment rate. Social diversity is limited in these areas, with a low proportion of professionals and a predominance of clerical and manual workers. The most challenging social circumstances are often concentrated here, with a considerable number of large and single-parent families, tenants and those living below the poverty line. Youth unemployment is particularly high in these areas.

The case of Lyon, the metropole, highlights this phenomenon. The map produced by the Lyon Urban Planning Agency shows that towns with a high density of priority neighbourhoods have youth unemployment rates of up to 33 per cent. Conversely, towns without any priority neighbourhoods are less affected by mass unemployment. The populations of QPVs have a higher proportion of people from immigrant backgrounds than the rest of France, two to three times that proportion. This, therefore, gives rise to other issues: access to education and language learning amongst young people, social exclusion, and difficulties in understanding the services available to them. Educational disadvantages and language barriers further restrict access to employment and everyday mobility. Lower driving licence ownership, lower car availability and reduced access to public transport contribute to lower levels of daily mobility. Thus, travel is infrequent: 20 to 30 per cent of the population in priority neighbourhoods only go out when necessary and make only essential journeys. Economic deprivation also limits access to leisure, employment opportunities and mobility because travelling itself represents a financial cost.

Residents of QPVs are therefore fairly sedentary due to limited resources and a lack of understanding, yet they are largely deprived of public services. Whilst QPVs are fairly isolated from state services, they do have other strengths. The voluntary sector is strong and, above all, essential to local life, as evidenced by its role in shaping public policy. It enables several things: it addresses the State's shortcomings in QPVs regarding public services, maintains strong social ties within neighbourhoods, and makes it easier to bring local issues to the attention of public authorities. Despite these difficulties, local associations play a crucial role in compensating for limited public services, supporting residents and acting as intermediaries with public authorities. However, their dependence on public funding often limits their autonomy. They are frequently in a precarious position despite the importance of the tasks entrusted to them (mediation, education, social integration).

The Etouvie Social and Cultural Centre illustrates these tensions between civic mobilisation and institutional dependence. During discussions on the launch of the 2014 National Urban Regeneration Plan, numerous community groups participated, as documented in AC Le Feu's report. This report, co-authored by Mohamed Mechmache, an educator, and Marie-Hélène Bacqué, an urban planner, was sent to Mr Lamy to highlight the needs of residents in priority neighbourhoods (QPV).



Priority neighbourhoods are also of interest to the media and politicians. Owing to their precarious economic and social situation and their large population, they attract significant attention from the political class. Figure 1 highlights an important point: employment and housing feature most prominently in discussions about working-class neighbourhoods (often accounting for nearly 60 per cent of all articles). Security, often associated with working-class neighbourhoods, has steadily declined as a proportion of total articles but has risen again in recent years, potentially linked to the urban riots following Nahel's death. The issue of mobility, meanwhile, emerged relatively late in the media and remains marginal in the debate despite its major importance for access to employment. Finally, another potential insight is that the press appears to be a good indicator of the public authorities' priorities. The figure shows that the overwhelming majority of the debate centred on housing during the Borloo Plan (Gallois, Nieddu, 2015). Conversely, housing took a back seat (-16 per cent) in favour of employment when François Hollande launched the employment laws (*emplois francs*). Similarly, in the year leading up to the National Front's second-round run-off in the 2002 election, the media focused on security (24 per cent of articles covered security and employment, and 26 per cent covered housing).

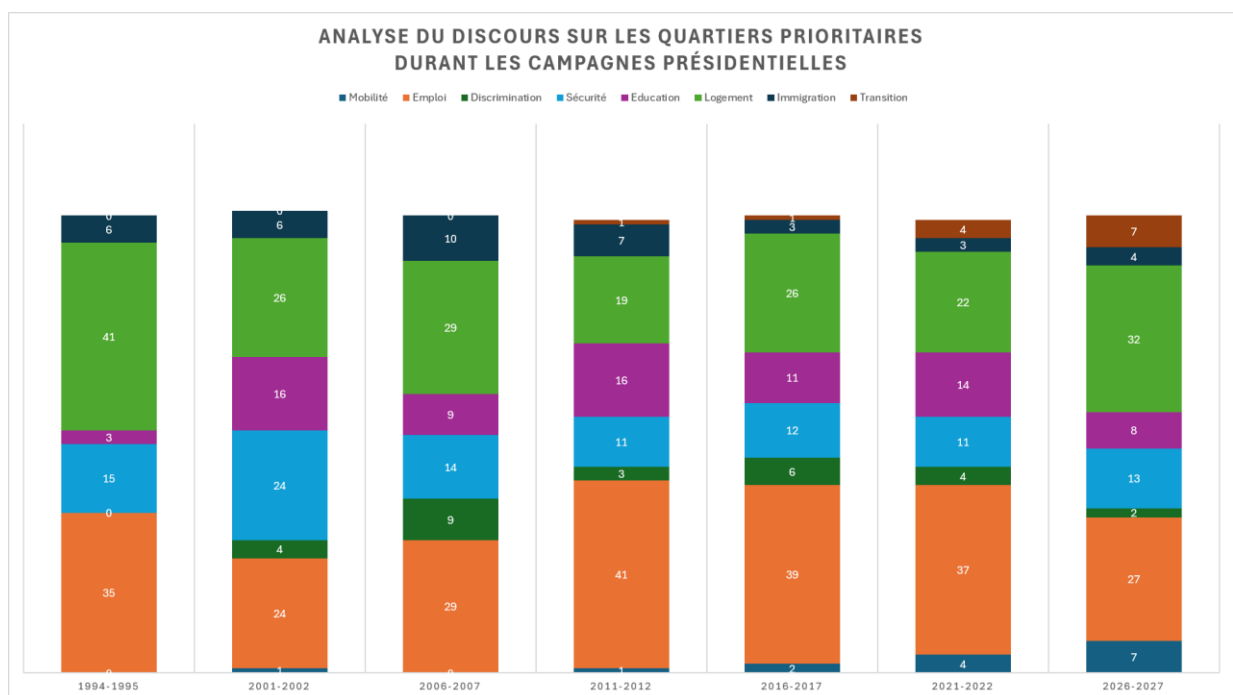


Figure 1 – Trends in the topics covered in press articles on priority neighbourhoods during presidential campaigns – Europresse data

3.2 Public policies and their impact on mobility in the suburbs

The term *urban policy* first appeared in the late 1980s. Prior to that, urban policy had focused on the neighbourhood level, an approach that many reports sought to move beyond through the 'quarrel over scales'. In this context, the drive for urban continuity and the development of autonomous neighbourhoods were a cause for concern. Creation of city contracts with a social cohesion component resulted in the development of the Solidarity and Urban Renewal Act (SRU), which introduced an inter-municipal allocation system for social housing (Kirszbaum, Epstein, 2010: 46). In these public policies, mobility was therefore focused on travel within neighbourhoods and had not yet been generalised. Mobility gradually gained prominence amid criticisms of a breakdown in social cohesion and a 'fragmented city', which began to concern the public authorities. However, this did not prevent certain metropolitan areas, such as the Lyon metropolitan area, from failing to develop heavy transport infrastructure linking high-density residential areas to the conurbation's centre.

Subsequently, social cohesion was placed at the heart of these ambitious policies. The Borloo Plan was the first large-scale initiative to address the effects of urban inequality. As part of its reforms, it established the National Agency for Urban Regeneration (ANRU), which is responsible for ensuring the effectiveness of urban policy. The



programme relied primarily on large-scale demolition and reconstruction to promote social mix and improve the physical environment of disadvantaged neighbourhoods. The SUZ (Sensitive Urban Zone) areas were portrayed as 'disadvantaged' neighbourhoods that the government wished to bring up to standard. In addition to forced residential relocation, this also involved infrastructure works to improve access. No consideration is given to the history of these neighbourhoods, to the promotion of their strengths, or even to residents' attachment to them. The systematic demolitions were reformed under the New National Urban Renewal Plan (NPNRU), in which public authorities sought to engage in more dialogue and involve residents in the initiatives, notably by creating 'project centres'. Although mobility appears among the programme's objectives, urban renewal remained primarily centred on housing and employment rather than mobility itself.

Mobility was not the primary objective of these large-scale urban renewal programmes, which focused mainly on housing, urban regeneration and social cohesion. However, during the same period, French transport policy underwent a profound transformation. As highlighted by Debizet (2004), it progressively shifted from a transport-planning paradigm to a broader mobility-management approach. This evolution was accompanied by a transformation in the expertise that supports public decision-making and a diversification of policy objectives beyond infrastructure provision. It is within this broader evolution that the main transport and mobility laws should be understood.

In 1982, the Pierre Mauroy government introduced the Framework Act on Domestic Transport (LOTI) (Saroli, 2015) in order to implement a "right to transport that enables users to travel under reasonable conditions of access, quality and price, as well as in terms of cost to the community, in particular through the use of a means of transport open to the public". The legislation places an emphasis on geographically disadvantaged populations ("Disadvantaged social groups, particularly those in island areas and remote or hard-to-reach regions of the national territory, may be subject to provisions tailored to their situation."). The issue of transport features in the Act and, with it, the emergence of the issue of mobility. Indeed, Article 2 includes "the right of users to be informed", which could be understood as the beginning of the consideration of the individual beyond infrastructure. The LOTI remains, however, first and foremost a law that defines the role of each public institution in mobility by presenting mobility as a joint effort between local authorities and the State. It provides for the introduction of urban transport plans (PDU).

This was followed in 1996 by the Act on Air Quality and the Rational Use of Energy (Belot, 1996). This Act radically changed the PDU's vision, giving it a much stronger environmental focus to reduce car use and develop public and sustainable transport, particularly to improve air quality, as set out in Articles 28 and 28-1. It also makes it compulsory to draw up a PDU within two years of the Act coming into force. The PDU thus becomes more than just an administrative tool; it is an environmental policy instrument aimed at reducing greenhouse gas emissions and air pollution, and at promoting alternatives to car travel (public transport, cycling, etc.). However, the effectiveness of the PDU is often questioned. The multitude of plans (Local Urban Development Plan (PLU), Territorial Cohesion Scheme (SCOT), Local Housing Plan (PLH) and Urban Transport Plan (PDU)) makes coordination difficult. There are also significant developments: the growing importance of mobility – "mobility is increasing through more frequent journeys over longer distances" – and the role of the State in addressing the lack of coherence between plans: *"Establishing a better balance within urban areas. This is impossible when housing, transport and planning policies are neither designed on the right scale nor in a way that is consistent with a genuine urban area development plan, one that takes social and territorial balances into account."*

Thus, following the SRU Act of 2000, the Urban Transport Plan has been strengthened and aligned with the Territorial Coherence Scheme (SCoT), thereby enabling better coordination between transport policies and territorial development. This development also reinforces the role of urban transport organising authorities (AOTUs). The development is mainly carried out by public inter-municipal cooperation bodies (EPCIs), now responsible for drawing up the PDUs. This evolution reflects a broader shift towards integrated mobility governance. Recent studies underline that accessibility depends not only on transport infrastructure but also on the coordination between land-use planning and transport policies, as fragmented urban development may reinforce territorial inequalities in mobility (Macsinka, 2025).

In 2010, under President Sarkozy's leadership, there was a desire to simplify transport management. The Transport Code was drafted with this aim in mind. Its preamble states: *"This Code therefore pursues two*



complementary objectives: to bring together, organise and clarify a fragmented and heterogeneous body of law, and to place this reorganised body within a framework that gives full effect to the founding principles defined by the aforementioned Act of 30 December 1982." It therefore brings together the various modes of transport by harmonising them. One objective stands out clearly: the desire to develop intermodalisation in urban transport. Indeed, this is the first requirement cited in the President of the Republic's report on the Act: *"a comprehensive transport policy establishing coordination of public authorities' policies, the promotion of intermodality, environmental protection and citizen participation"*. The report also details the responsibilities of the various stakeholders in the mobility sector: the State, the Transport Regulatory Authority, and the port authority.

This decentralisation of the State's powers continued with the NOTRe Act, which focused on rail transport, and then the Mobility Orientation Act (LOM) in 2019, which completed the devolution of powers to local authorities. Whilst this approach has evolved gradually – as evidenced by the differences between the PNRU and the NPNRU on issues of dialogue and individuals – the LOM Act also reflects this change by building on new proposals: financial incentives for sustainable transport, financial assistance for driving licences, and the development of innovative solutions. However, the LOM also indirectly affects QPVs. Indeed, the LOM broadens the scope of action on solidarity-based mobility: *"funding for voluntary organisations promoting 'inclusive mobility' to develop and sustain support for mobility among certain vulnerable groups, with services going beyond mobility advice: learning to ride a bike, community garages."*

Overall, the evolution of French transport policy illustrates a gradual shift from infrastructure provision towards a broader understanding of mobility that combines accessibility, territorial planning, and individual support. This evolution provides the institutional context for the emergence of inclusive mobility initiatives, which are examined in the following sections. This evolution is consistent with broader European trends in transport governance, where sustainable mobility policies increasingly combine multimodal transport, accessibility, digitalisation (Mobility as a Service) and social inclusion rather than focusing exclusively on infrastructure provision (Tánczos, 2025).

3.3 From access to transport to mobility capacity: understanding mobility inequalities in priority neighbourhoods

This paper examines the history and specific characteristics of priority neighbourhoods and their role in public policy. Whilst there are many forms of inequality within these neighbourhoods, this section will now focus on one in particular: mobility inequality.

3.3.1 Improving access as the primary response to inequalities in mobility

Priority neighbourhoods, the majority of which are drawn from ZUPs, are situated mainly on the outskirts of major urban centres and are difficult to access. As public transport is often concentrated in the more densely populated city centres, QPVs are often less well served than the rest of their metropolitan area. However, residents of these neighbourhoods are also those with the least access to a car: 60.6 per cent hold a driving licence, compared with 85 per cent in the rest of France. Due to its high cost, a driving licence is a scarcer resource among residents who are, nevertheless, more dependent on it. Goudie (2000) has highlighted the importance of – and indeed the heavy reliance on – cars amongst residents of QPVs by demonstrating that, despite this disparity in driving licence ownership, a working-class man is more likely to use his car when he lives in a QPV. This issue, therefore, raises the question of the degree of isolation.

This isolation is often physical, caused by roads, 'impassable' areas, such as cemeteries or airports, and other obstacles, or by topographical features such as steep slopes. This can therefore create a strong sense of separation from the rest of the city and discourage residents from leaving the neighbourhood. This isolation can also make it more difficult to provide efficient public transport and force people to take long detours to reach urban centres. However, where these barriers are significant, such isolation is, in extreme cases, largely offset by public authorities, which sometimes step up efforts to improve access to public transport.

However, one point clearly highlights a major difference in mobility between residents of priority neighbourhoods and those in other neighbourhoods. Goudie (2000) has, in fact, shown that residents of priority neighbourhoods



spend the same amount of time travelling as other residents. However, the distance travelled is shorter, except for small urban units (Goudie (2000) attributes this difference to the fact that the sample of urban units with a population of less than 50,000 consists of areas on the outskirts of major urban centres).

Early public policies focused primarily on infrastructure. It was not until the 1990s that other forms of support began to emerge. In 1991, social driving schools emerged with the 'Permis pour l'avenir' initiative in Nanterre. The stated aim of the initiative was to promote social integration in priority neighbourhoods by enabling the most vulnerable people to obtain a driving licence. Then, in the 2000s, 'mobility centres' and the role of mobility adviser emerged. However, the government was slow to invest heavily in these schemes. In 2024, whilst billions are invested each year in infrastructure, the Inclusive Mobility Laboratory estimates 'the economic value of inclusive mobility at 150 million euros'. Support organisations still rely heavily on volunteers (50 per cent use them), and 14 per cent of their working time is spent seeking funding. This support has helped 200,000 people, compared with an estimated 5 to 7 million who need such assistance. The scale of the gap between mobility support and spending on new infrastructure raises questions.

In the Lyon metropolitan area, investment in new infrastructure in 2026 amounts to 1.057 billion euros. The development of tram lines is quite costly, and the introduction of the T9, T10, and TB12 lines, as well as the extension of the T6 line, is significantly driving up costs. It is claimed that, once these projects are completed, investment levels are expected to fall again.

However, whilst infrastructure development is essential for providing residents with access across the region, mobility support is irreplaceable, particularly in priority neighbourhoods, where rates of employment, language proficiency, driving licence ownership and car ownership among households are lower. The Lyon Metropolis offers personal financial assistance, socially responsible pricing, the expansion of the 'free-vélo' scheme, and the development of cycling schools. However, the investment is much lower. The Mobility Inclusion Scheme (DMI), with a budget of 150 million per year, is estimated at 400,000 per sector – less than 0.3 per cent of the budget allocated to developing new infrastructure.

3.3.2 Inequalities in mobility beyond social isolation

Gender inequalities in mobility are not unique to the "suburbs", but they are sometimes particularly pronounced there. This is already evident in the proportion of immobile people. The Goudie (2000) survey reveals a striking finding: women in the "suburbs" of the Paris urban area are twice as likely to be immobile as those in other areas. Similarly, outside Paris, there is a 4% gap compared with the rest of the urban area's population, even though no such gap is observed between men in priority neighbourhoods (QPVs) and the rest of the urban area. There are several explanations for these results. Firstly, the rate of economic inactivity is higher amongst residents of QPVs, and even higher amongst women. This therefore implies a reduction in commuting and a more general decline in mobility (half the distance travelled compared with those in employment). Furthermore, households in QPVs have, on average, fewer motor vehicles: whilst the proportion of households owning a motor vehicle is the same as outside QPVs, few households own two motor vehicles. Consequently, one of the two partners often has to give up driving, with women disproportionately bearing the burden of this sacrifice. As a result, they quite quickly exceed their daily 'transport budget' (travel time budget) because public transport is far less efficient, and so they do not venture out again after making essential journeys. In addition to this difference in usage, there is also a difference in objectives. Indeed, women play the leading role in care-related travel, even when their husbands are not at work. This role therefore accounts for a large proportion of their travel, once again reducing their daily 'transport budget' by taking up a significant part of their daily lives. This time spent on accompanying others is therefore time not spent on personal travel, such as commuting to work or other activities. Whilst gender-based inequalities do exist, other factors also influence mobility. Among these, age is a notable example.

Oppenchaim (2013) and Gallou (2021) have both worked on typical profiles of priority neighbourhoods. The first example concerns the approach to children. Various fairly typical profiles may emerge, for example, those of 'protected' girls. These children, the majority of whom come from minority backgrounds and socio-economically vulnerable families, grow up under parental pressure that leads them to fear the neighbourhood in which they live. The children, therefore, associate their environment with danger and are more often less mobile. This obviously has



a significant impact, as mobility is acquired through experimentation and repetition. These children, therefore, fall significantly behind in mobility. This has an even greater impact as they are not necessarily well integrated into the local area around their homes. A contrasting profile also emerges. Often female, this profile of 'flâneuses' (strollers), as described by Oppenchain (2013), is characterised by a high degree of mobility. Their rejection of the neighbourhood is reflected in their increased use of public transport. Repeated experiences enable a better understanding of the transport network and social norms. The other rather distinctive profile is that of immigrants, including a group that Gallou (2021) has focused on: elderly immigrant women. Gallou (2021) describes this group as often finding themselves in difficult circumstances due to precarious employment, limited language proficiency and poor health. As a result, they often rely more on their local community than on public institutions, which are too complex to understand. Although these profiles are fairly typical of QPVs, they have still been studied relatively little. Few public policies take these specific circumstances into account. These profiles raise questions about the effectiveness of public services in QPVs.

These profiles prompt us to question the economic model of mobility. Indeed, what is the point of focusing on new, large-scale infrastructure projects if the people that must be helped are not actually helped in the end due to a lack of personalised support? This question leads us to the final section of the article, namely, the response to the specific problem faced by priority neighbourhoods regarding residents' mobility.

3.3.3 Towards a capability-based approach to mobility

This paper has therefore examined mobility inequalities and their impact on priority neighbourhoods (QPVs). These inequalities stem from a combination of factors that reduce travel and its efficiency. Firstly, there is physical access to transport, the State's primary objective in these public policies, which have brought about the construction of roads, buses, trams and even the underground to provide access to transport. Secondly, as seen in the previous section and in relation to the typical profiles of QPVs, there is the issue of transport acceptance. A fear of travelling or a lack of knowledge of the social norms typical of public transport can lead to journeys being cancelled or, at the very least, restricted. Finally, the concept of competence or the development of 'mobility capital' becomes significant. Even if the conditions for access and mobility plans are met, one still needs to know how to get around. Without this competence, a very dense network could reinforce the feeling of exclusion (Maguer et al., 1997). This competence can be seen as a form of capital in its own right, in the Bourdieusian sense. Kaufmann points out that the ability to move about, to be mobile, depends largely on this capacity. Thus, the objective – following the major policies on access to public transport implemented by the State and metropolitan authorities – would be to develop this capacity in order to reduce inequalities in mobility (Kaufmann et al., 2004).

These inequalities affect not only daily life but also work. The ability to move around, and indeed to have lived abroad, offers an added advantage during the recruitment process. This can be the case in research professions or within international organisations (e.g., Médecins Sans Frontières), where mobility serves as a springboard for promotion (Joxe, 2022).

Thus, providing everyone with the ability to get about in their daily lives and, potentially, to move abroad could help to rebalance each person's mobility capital and facilitate access not only to employment but also to more skilled jobs and promotions.

As part of this initiative, the Vienna and Gartempe Community of Communes has developed the concept of urban walking tours. The local authority chose this approach to promote active travel, with the walk comprising both theoretical and practical components. However, this phenomenon is also evident in priority neighbourhoods. The exploratory walks organised by SYTRAL and Keolis in the Lyon metropolitan area provide a better understanding of the difficulties women face when travelling in areas with higher levels of insecurity (Famy et al., 2008). This approach, which aims to tackle gender inequalities, could be used to examine various forms of inequality (age, family situation, etc.) and to take stronger and more effective action through public policy.

In Essonne (France), it was the public transport operator (TICE) that sought to address transport issues. To this end, it sent staff to primary and secondary schools to help younger pupils understand the transport network and make them aware of the services they were entitled to. This initiative has led to an increase in the number of passengers and in the number of people accessing the network's services, including income- or age-based season ticket fares.



These approaches show that it is possible to view mobility in a different light than purely state-led action. Local initiatives – whether public or private, professional or voluntary – are possible, and each can help us address different issues and reach a wider audience.

3.4. The city's priority neighbourhoods: a key urban arena for political life

The term *priority neighbourhood* (Quartiers Prioritaires de la Politique de la Ville, QPV) is a relatively recent concept in French urban policy. It first appeared in the Lamy Act, named after the Minister for Urban Affairs, of 21 February 2014. QPVs are defined in Article 5 by their location within urban areas and are characterised by a disparity in economic and social development, assessed based on residents' incomes. Therefore, these are the country's most socio-economically disadvantaged urban areas, where public intervention is considered necessary. In practice, the State designates neighbourhoods as 'priority' solely on the basis of their residents' income. Whilst this term is new in the history of urban policy, the concept itself dates back much further. The desire to identify areas facing difficulties within public policy stems in particular from the history of working-class neighbourhoods under the Fifth Republic.

The article reveals the transformation of the French public policies on mobility in priority neighbourhoods. Policies were initially focused on urban regeneration and housing improvements, when mobility was a focal issue. At first, mobility was understood as access to transport with the development of roads, buses, tramways and subways.

However, the literature and institutional reports reviewed in this paper show that physical accessibility alone does not explain the mobility difficulties experienced by QPV residents. Lower driving licence ownership, reduced access to private vehicles, educational disadvantages, language barriers and limited knowledge of transport systems all contribute to restricting daily mobility despite the availability of transport infrastructure.

These findings also suggest that existing accessibility indicators based on travel time, network density or infrastructure provision may not fully capture mobility inequalities. Individual factors such as driving licence ownership, mobility skills, confidence in using public transport, language proficiency and knowledge of available services significantly influence residents' ability to access opportunities. Integrating these behavioural and social dimensions into accessibility assessment could therefore improve transport engineering models and provide a more comprehensive understanding of mobility exclusion.

Since the 2000s, and more clearly following the Mobility Orientation Act (LOM) of 2019, public policies have progressively incorporated a broader conception of mobility based on personalised support. The emergence of mobility advisers, social driving schools, cycling schools and mobility inclusion programmes illustrates this transition from transport provision towards mobility capability. These initiatives aim to provide more than access to transport by developing residents' confidence and autonomy in their mobility.

From an evaluation perspective, the effectiveness of inclusive mobility policies could be assessed through multidimensional indicators rather than infrastructure provision alone. Possible indicators include driving licence acquisition, frequency of daily trips, access to employment, participation in education or training, autonomy in public transport, and perceived accessibility. Such indicators would better reflect the objectives of inclusive mobility policies and facilitate comparisons with traditional infrastructure investments.

Nevertheless, this transition remains incomplete. Infrastructure remains the largest share of public expenditure on mobility, and inclusive mobility and social initiatives are still struggling to secure financing from public actors. As a result, mobility inequalities continue to persist despite significant improvements in transport infrastructure.

Overall, this article supports the argument that mobility policies are increasingly moving from an infrastructure-centred model towards a capacity- and inclusivity-centred approach. However, achieving mobility inclusion will require greater investment in personalised support alongside continued improvements in transport accessibility.



4. Conclusion

This paper examined the evolution of French public policies addressing mobility in priority neighbourhoods, from the emergence of urban policy to the recent development of inclusive mobility initiatives. It has been shown that mobility inequalities cannot be explained solely by deficiencies in transport infrastructure but result from the interaction of social, economic, educational and territorial inequalities.

The analysis demonstrates that French public policies have progressively broadened their understanding of mobility. Whereas early interventions concentrated on urban renewal and transport infrastructure, more recent policies increasingly recognise the importance of developing residents' mobility capabilities through personalised support and local initiatives. This evolution reflects a shift from ensuring access to transport towards enabling individuals to use mobility effectively.

The main contribution of this paper is to bring together the historical evolution of French urban and transport policy and the emerging concept of inclusive mobility within a single analytical framework. It highlights the growing importance of capability-based approaches while underscoring the persistent imbalance between infrastructure investment and mobility support.

This research nevertheless has several limitations. It relies primarily on documentary analysis, scientific literature and institutional reports and does not include primary empirical fieldwork with residents or mobility professionals. Likewise, the paper does not assess the operational effectiveness of inclusive mobility initiatives through quantitative accessibility modelling or performance indicators. Future research could therefore combine qualitative fieldwork with transport engineering methods in order to examine how residents experience inclusive mobility measures in their daily lives and to evaluate their effectiveness using multidimensional indicators. Comparative studies involving other European countries would also help assess the transferability of the French policy model to different institutional and urban contexts.

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Design, sizing, and feasibility analysis of a hybrid renewable generation system for the self-sufficiency of an off-grid house

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Abstract

Rural isolation from national electricity grids represents a persistent infrastructure challenge in Mediterranean mountainous regions, where isolated dwellings have traditionally depended on generators with prohibitive environmental and economic costs. This study proposes a modular engineering framework for the design and sizing of hybrid off-grid renewable generation systems, applied as a case study to a residential property in El Pla de La Llacuna (Villalonga, Valencia, Spain). The methodology develops a decoupled catalogue of four independent energy modules – solar photovoltaic (PV), micro-wind, geothermal, and electrochemical storage – each governed by strict technical boundary conditions that filter site suitability. The framework was applied through a multi-step process: resource characterisation using the PVGIS-SARAH3 database and hyper-local AVAMET meteorological data; load profile construction via a bottom-up appliance inventory; and iterative system sizing validated through computational simulation. Three energy supply scenarios were simulated and benchmarked against a 100% fossil-fuel baseline. The results demonstrate that a hybrid solar-wind configuration comprising 8 photovoltaic panels (4.28 kWp), 6 LiFePO₄ batteries (28.8 kWh), and a 10 kW Vertical Axis Wind Turbine (VAWT) constitutes the optimal solution for this site, achieving total annual energy self-sufficiency with a capital expenditure of €12,328, a net present value (NPV) of €337,406, a return on investment (ROI – return on investment) of 34.07, and a payback period of 0.323 years. Geothermal exploitation was rejected due to geological and logistical constraints, while continuous wind generation was discarded as a primary source due to insufficient mean velocities, though transient gusts up to 73.4 km/h were successfully harvested as a winter supplementary resource.

Keywords: off-grid systems; hybrid renewable energy; photovoltaic sizing; VAWT; LiFePO₄ storage; modular design; energy self-sufficiency; PVGIS; rural electrification

1. Introduction

The global transition toward decentralised, renewable energy systems has shifted from theoretical aspiration to technical and environmental necessity, particularly in geographically isolated regions. In the Mediterranean basin, and specifically within mountainous inland territories, residential properties frequently face a critical infrastructure challenge: the complete absence of a reliable connection to the national electricity grid. Historically, these isolated off-grid dwellings have depended on internal combustion generators to meet energy demands – a model that entails severe drawbacks, including high operational costs, logistical challenges in fuel supply, noise pollution, and significant greenhouse gas emissions.



Theme	Key finding	Population / system focus	Citations
Baseline architecture	The most established off-grid residential architecture is PV + wind + battery , typically coordinated through inverter and charge-control components; some studies add diesel, hydrogen, or fuel cells to increase autonomy and reliability.	Off-grid houses, remote communities, rural electrification systems	(Akinyele, Rayudu, Nair, 2016); (Mohammadnezami et al., 2015); (Sahu, Jena, Sahoo, 2021), (Engin, 2013), (Jadhav, Patil, 2020), (Al-Quraan, Al-Mhairat, 2024), (Rathod, Balaji, 2025), (Ahmad, Farzaneh, 2024)
Design logic	Hybridisation usually improves reliability and renewable contribution relative to single-source systems, but the best mix depends on local solar-wind complementarity and the household load profile.	Residential and rural hybrid energy systems	(Rathod, Balaji, 2025), (Nizam et al., 2025), (Bicks, 2021), (Behmounesi et al., 2024), (Tutkun, Çelebi, Bozok, 2017)
Resource assessment	Recent sizing studies increasingly use PVGIS, Meteonorm, NASA POWER, GIS screening, and TMY/hourly weather series rather than simple averages.	Off-grid PV-wind sizing studies	(AbdelHadi et al., 2025), (Alotaibi, Alturki, 2025), (Petrollese, Seche, Cocco, 2019), (Mayer, Szilágyi, Gróf, 2020)
Wind/PV conversion methods	Annual yield estimates often convert weather inputs using module-plane irradiation models for PV and hub-height extrapolation plus turbine power curves for wind.	Simulation-based hybrid system sizing	(Petrollese, Seche, Cocco, 2019), (Mayer, Szilágyi, Gróf, 2020), (Chen, Aidong Yang, Bañares-Alcántara, 2021)
LiFePO4 storage	LiFePO4 is increasingly preferred for off-grid storage because of long cycle life, high efficiency, deep-discharge tolerance, thermal stability, and fewer replacements than lead-acid options.	Off-grid PV and hybrid storage systems	(Shimomura, Mochizuki, Takano, 2016), (Chen et al., 2021), (Eteiba et al., 2018), (Layadi et al., 2023), (Abed, Maheri, 2025)
Battery caveats	LiFePO4 performance still depends strongly on temperature, charge/discharge rate, SOC window, and degradation assumptions.	Stationary battery studies, microgrids, off-grid storage	(Zhao et al., 2020), (Abd El-Sattar, Kamel, Hassan, 2025), (Wen, Zhao, Zhang, 2020), (Yang et al., 2025)
Sizing methods	HOMER, GA, PSO, MATLAB/Simulink, and multi-objective metaheuristics are the dominant sizing approaches, usually minimising NPC, TAC, COE/LCOE while enforcing LPSP/DPSP/autonomy constraints.	Off-grid houses and small communities	(He et al., 2023), (Fares, Fathi, Mekhilef, 2022), (Thirunavukkarasu, Lala, Sawle, 2023), (Gicevskis et al., 2021), (Li, 2019), (Forrousso et al., 2024), (Das, 2020)



Feasibility metrics	The standard feasibility indicators are LCOE/COE, NPC, reliability, unmet load or LPSP, renewable fraction, autonomy, and sensitivity analysis.	Rural electrification case studies	(Nguyen et al., 2024), (Fosso Tajouo, Tiam Kapen, Djanna Koffi, 2023), (Viridyet al, 2026), (Diyono et al, 2026), (Ghaziasgar, Pourfayaz, Vaziri Rad, 2025)
Central trade-off	Higher self-sufficiency and stricter reliability generally require more storage and higher capital cost; full off-grid autonomy is often more expensive than grid-connected or backup-assisted options.	Off-grid vs on-grid / diesel-assisted comparisons	(Ahmad, Zhang, 2021), (Bullen et al., 2025), (Caglayan, 2025), (Rajbongshi, Borgohain, & Mahapatra, 2017), (Kolhe, Ranaweera, & Gunawardana, 2013)

A bibliometric analysis of 44 peer-reviewed documents retrieved from ScienceDirect (2021–2026) using VOSviewer v.1.6.20 (Van Eck, Waltman, 2014) for co-occurrence analysis identified three strategic research pillars sustaining the development of decentralised systems: thermal and geothermal cluster technologies, building-integrated energy efficiency, and the photovoltaic-storage backbone underpinning electrical autonomy (*Figure 1*). These pillars highlight the current knowledge gap: the lack of replicable, modular design methodologies adaptable to heterogeneous rural environments.

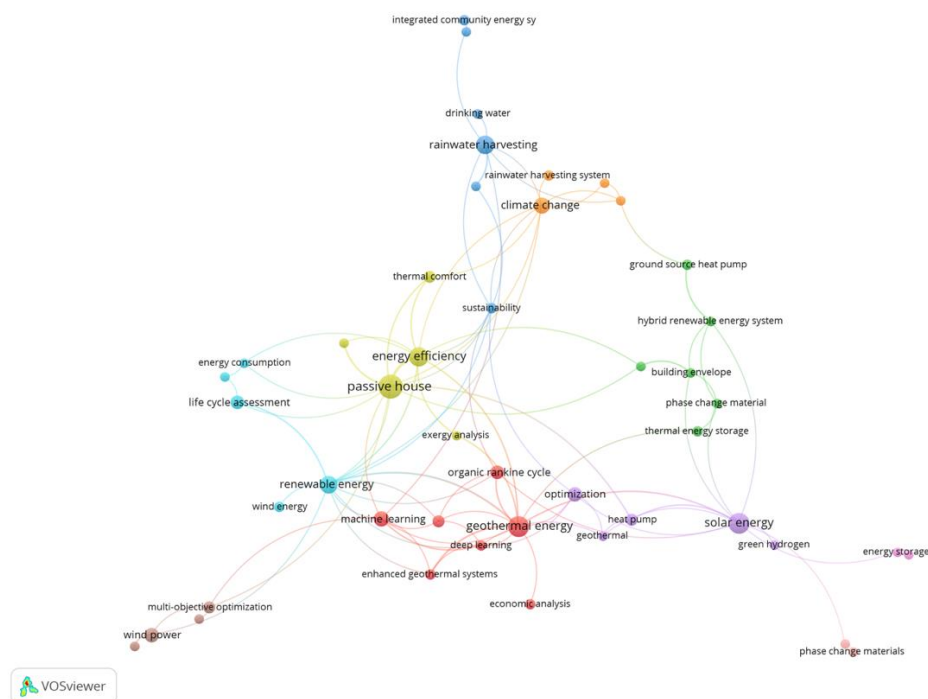


Figure 1. Bibliometric network map of keyword co-occurrences in off-grid hybrid energy literature.

Source: Own elaboration based on data extracted from ScienceDirect via VOSviewer (2026).

This study addresses that gap by developing a modular engineering framework composed of four independent energy modules – Solar Photovoltaic (Module A), Micro-Wind Generation (Module B), Geothermal Systems (Module C), and Electrochemical Storage (Module D) – each governed by strict technical entry thresholds. Unlike traditional single-point engineering solutions, the proposed catalogue is designed to be adaptable and scalable, enabling different configurations to be assembled to suit the specific topography, climate, and budget of any given rural site. To demonstrate the framework's



applicability, the methodology is applied to a permanent residential property in El Pla de La Llacuna (Villalonga, Valencia, Spain), a representative case of an isolated Mediterranean mountain dwelling.

It is hypothesised that a hybrid photovoltaic-wind configuration, sized and optimised using the modular filtering methodology, can achieve complete year-round energy self-sufficiency for the target household, with a more favourable lifecycle cost profile than both conventional fossil-fuel baselines and purely solar renewable alternatives.

2. Methodology

The methodology is structured in four sequential phases: modular library definition, site resource characterisation, load profile construction, and multi-scenario iterative sizing, data collection for simulation and feasibility study.

2.1 Modular library and entry thresholds

Each energy module was defined with operating principles, selected technology standards, and mandatory boundary conditions for site approval.

Module A (Solar PV): Monocrystalline PERC technology (Wang et al., 2024) was selected for its superior efficiency (20–23%) and low-light performance. The critical entry threshold was defined as a minimum of 2.5 Peak Sun Hours (PSH) in the worst month, as extracted from the PVGIS-SARAH3 database. The structural tilt was mathematically optimised for the winter solstice, using the formula $\beta = \varphi + 15^\circ$, yielding a fixed angle of 54° for the target site's latitude ($\varphi = 38.86^\circ\text{N}$).

Module B (Micro-Wind): A Vertical Axis Wind Turbine (VAWT) architecture was selected over an HAWT for its omnidirectional wind-capture capability under turbulent mountain conditions. The baseline entry threshold required a minimum annual average wind speed of ≥ 3.0 m/s at hub height to qualify as a continuous generation source (Li et al., 2022; Akan, Akan, 2022; Wise et al., 2022).

Module C (Geothermal): Shallow geothermal exploitation via a Ground-Source Heat Pump (GSHP) closed loop was evaluated. Entry criteria included adequate subsoil thermal conductivity ($1.5\text{--}3.0$ W/(m·K)), sufficient surface area for horizontal trench collectors or drilling access for vertical boreholes, and regulatory compliance regarding protected aquifer zones (Tarnawski et al., 2009; Bucci et al., 2017; De León-Ruiz et al., 2022; Maghrabie, Abdeltwab, Tawfik, 2023; Tang et al., 2023; Dong et al., 2024).

Module D (Storage): Lithium Iron Phosphate (LiFePO_4) technology was standardised as the electrochemical storage core, selected for its exceptional cycle life ($> 4,000\text{--}6,000$ cycles at 80% DoD), high round-trip efficiency ($>95\%$), and thermal stability. A 48 V nominal bus architecture was specified to minimise cable losses (Alipour et al., 2020; Kavaliauskas et al., 2023; Roy et al., 2024; Assi, Amer, 2025).

2.2 Site resource characterisation

The target property (Fig. 2.) is located at $38^\circ 51' 39.3''$ N, $0^\circ 11' 46.0''$ W, at approximately 600 m above sea level, within the Safor mountain range. Solar resource was quantified via two sequential PVGIS-SARAH3 simulations: a baseline optimised-slope run, and a definitive calibrated run at the engineered 54° angle. Anemometric data were extracted from the AVAMET official network station Vilallonga – La Llacuna / est (separated from the property by a few metres within the same microclimatic boundary layer), covering a full annual cycle from April 2025 to March 2026. Geothermal viability was evaluated through geological characterisation of the local Prebetic subsoil system (AVAMET, n.d.; Martínez del Olmo, 2021).

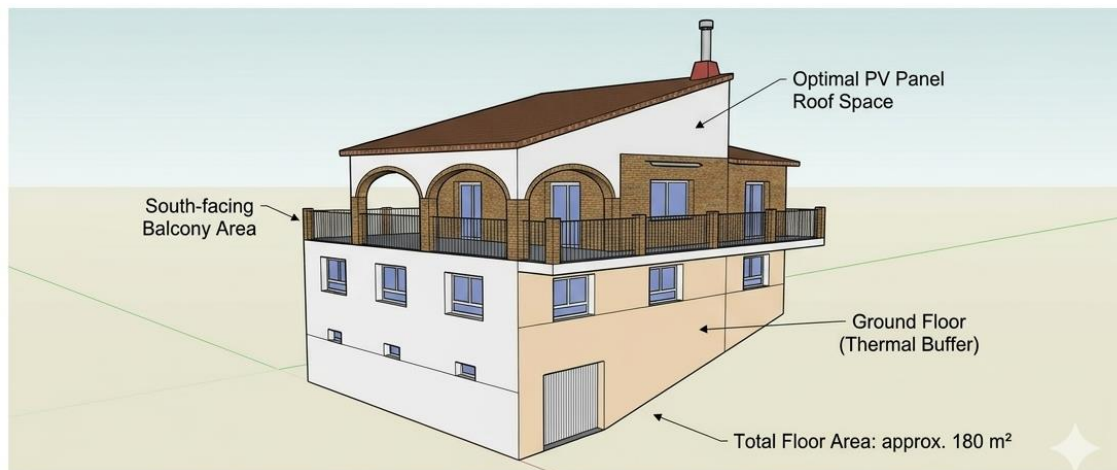


Figure 2. SketchUp 3D digital model and spatial breakdown for solar deployment analysis (Own elaboration, 2026).

2.3 Load profile construction

A dual-methodology approach was employed. First, a top-down municipal baseline was compiled from the Datadis national electricity distribution database (aelēc, n.d.) for Villalonga (April 2025 – March 2026). Second, a bottom-up analytical model was developed from the target household's specific appliance inventory, segmenting demand into a Fixed Consumption Core (7,720 Wh/day) and a Seasonal Variable Load (~900 Wh/day). Twelve monthly seasonal correction factors were applied to capture the full-year environmental variation, generating a definitive average daily consumption of ~8,620 Wh/day. Thermal, cooking, and domestic hot water loads were explicitly excluded from the electrical scope, as they are fully satisfied via biomass and LPG infrastructure (Figure 3).

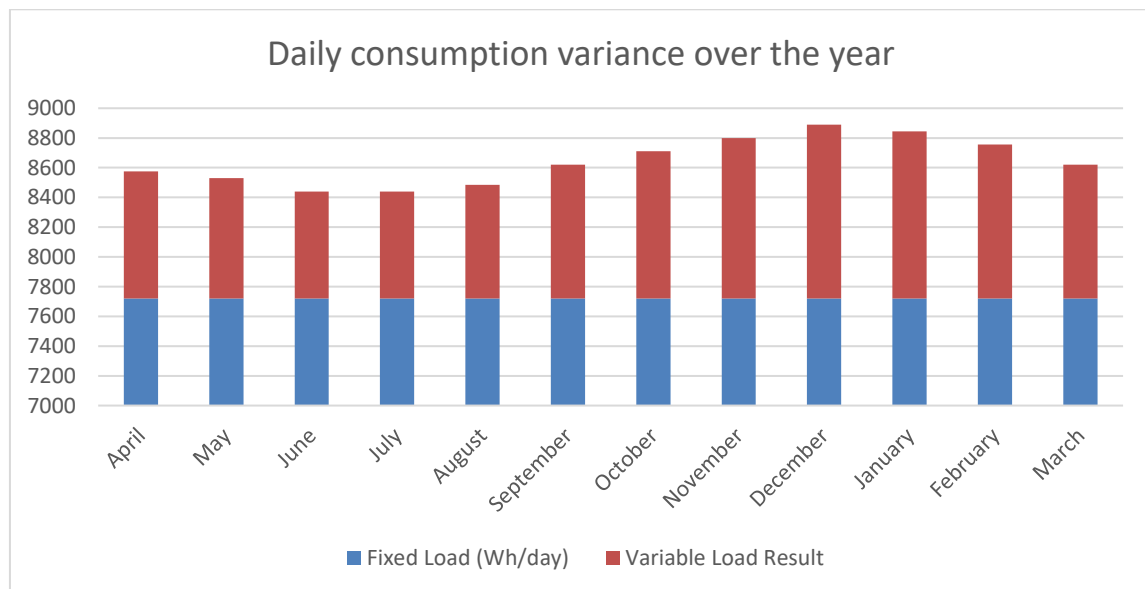


Figure 3. Domestic electrical load curve.

2.4 Scenario sizing and simulation

Four technical scenarios were sized and validated. The primary sizing algorithm used the Worst Month Method, applying the December critical daily demand ($E_d = 8,890$ Wh/day) and local PSH to calculate the required photovoltaic peak power (P_{pv}) and battery capacity (C_n). Computational validation was performed using the PVGIS Off-grid PV simulation tool (EC-JRC, n.d.), with a predefined acceptance criterion of 1%–5% of days with empty battery annually, and a strict maximum



Depth of Discharge (DoD) cutoff of 85% (15% State of Charge (SoC) floor). Financial viability was evaluated over a 10-year lifecycle using Net Present Value (NPV), Return on Investment (ROI), and Time of Return (TOR), applying a 5% discount rate and a 4% annual fuel price escalation to account for Eurozone inflation and carbon pricing trends.

3. Results

This section presents the results from applying the proposed modular engineering framework to the selected off-grid residential case study in Villalonga, Spain. The analysis combines site-specific resource assessment, technical system sizing, computational validation, and financial evaluation to determine the most suitable renewable energy configuration to achieve year-round energy self-sufficiency. The results are interpreted in relation to the predefined technical thresholds established for each energy module and the study hypothesis regarding the superiority of a hybrid renewable solution.

The results are organised in three stages. First, the local solar, wind, and geothermal resources are assessed to determine the feasibility of each technology module under the site's environmental and logistical conditions. Second, the technical performance of the evaluated energy scenarios is analysed, including energy balances, reliability indicators, and the contribution of complementary renewable sources. Finally, a comparative financial assessment is presented, benchmarking the alternative system configurations against the conventional fossil-fuel baseline through capital costs, operating expenditures, net present value, return on investment, and payback performance.

3.1 Site resource assessment

The definitive PVGIS simulation at the calibrated 54° tilt angle yielded a total annual in-plane irradiation of 1,897 kWh/m² and an annual electricity output of 1,660 kWh per installed kWp. The critical design month of December registered 4.52 PSH/day, exceeding the Module A minimum threshold of 2.5 PSH by 80.8%. Module A was therefore formally approved as the primary generation source.

Wind resource analysis revealed a very low annual mean velocity of 1.12 m/s (4.03 km/h), well below the 3.0 m/s continuous generation threshold. Consequently, Module B was rejected as a primary generation source. However, transient gust analysis demonstrated intense seasonal peaks of up to 73.4 km/h (November), with the winter quarter recording persistent gusts between 43.9 and 64.4 km/h. Module B was conditionally approved as an auxiliary transient support asset.

Module C (Geothermal) was definitively rejected on two grounds. First, the highly fractured Mesozoic limestone subsoil of the Prebetic system (Martínez del Olmo, 2021) presented low moisture retention and posed severe mechanical drilling challenges, requiring heavy rotary-percussive rigs that could not transit the narrow, unpaved mountain access roads to the plot. Second, the shallow leptosol soil depth profile (rarely exceeding 0.5 m before striking bedrock) rendered horizontal trench collectors economically unviable.

3.2 Scenario technical performance

Scenario 0 (100% ICE Generator) The Genergy Creta ATS 7.5 kW fossil fuel generator, operating continuously 24 hours/day for 365 days, consumed 22,776 litres of fuel annually (Leroy Merlin, n.d.). The cumulative 10-year expenditure reached €433,570, establishing the financial baseline.

Scenario 1 (100% Solar PV – 10 Panels, 8 Batteries) Preliminary analytical sizing yielded a target of 3.41 kWp and 35.09 kWh. Commercial hardware selection (JA Solar 535W TOPCon and Pylontech US5000 modules (Autosolar, n.d. f, b)) required rounding to 7 panels, which was subsequently scaled up to 10 panels (5.35 kWp) and 8 batteries (38.4 kWh) to eliminate a December localised failure rate of 10.2%. The definitive PVGIS simulation confirmed a global annual empty-battery probability of 0.58%, with December reduced to 0.5%. The monthly energy balance recorded a surplus for 11 of 12 months, with the only deficit in January (−51.20 Wh/day, representing less than 0.6% of daily demand).

Scenario 2 (Hybrid Solar-Wind – 8 Panels, 6 Batteries, 1 VAWT) The photovoltaic array was strategically downsized to 8 panels (4.28 kWp) and the battery bank to 6 units (28.8 kWh), with the TESUP Atlas 10 kW VAWT (TESUP, n.d.) integrated to compensate for winter deficits. The pre-wind solar-only simulation identified energy shortfalls in January



(−207.60 Wh/day), March (−69.50 Wh/day), November (−150.60 Wh/day), and December (−143.60 Wh/day). Dynamic analysis of a single hour of transient gust exploitation showed that even brief wind events during these months yielded sufficient energy to eliminate all deficits: November (850 Wh from a 73.4 km/h gust), December (220 Wh from 43.9 km/h), January (580 Wh from 60.5 km/h), March (610 Wh from 62.3 km/h). The final hybrid monthly balance demonstrated positive net generation for all 12 months (*Figure 4*).

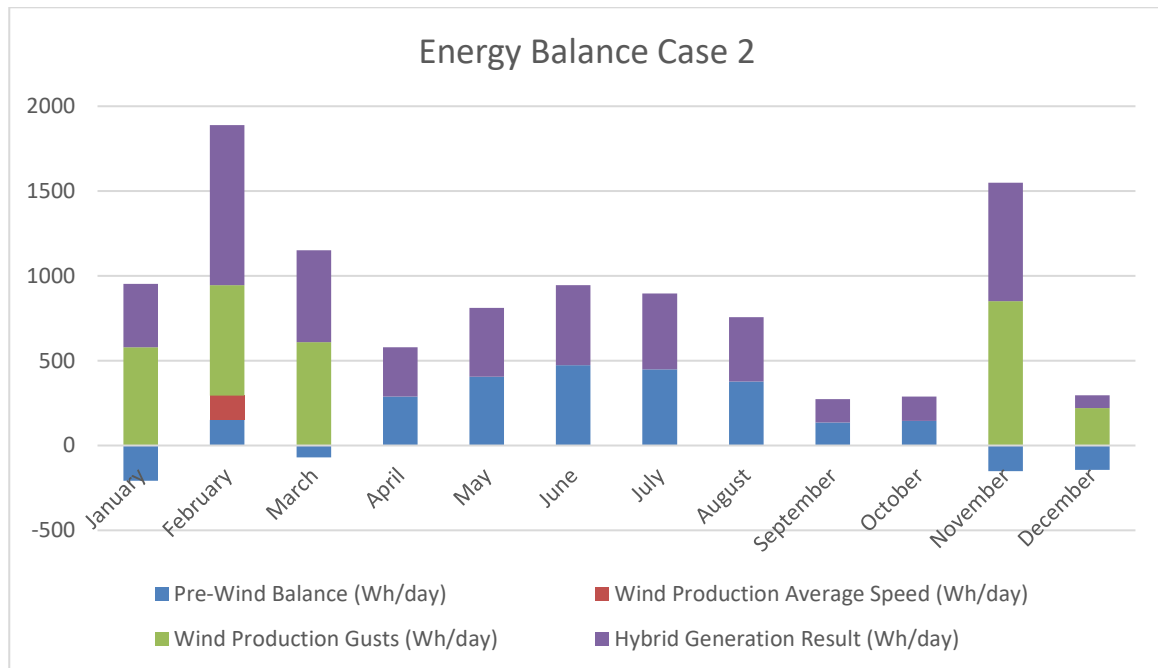


Figure 4. Post-wind energy balance.

The same downsized solar architecture was maintained, replacing the VAWT with the fossil-fuel generator. The generator operated exclusively on days of battery depletion, totalling approximately 10.6 days/year (conservatively rounded to 11), and consumed 686.4 litres of fuel annually – a 97% reduction compared with Scenario 0. However, the OPEX remained penalised by recurrent fuel costs escalating at 4% annually, and a combined maintenance bill of €870/year.

3.3 Financial comparative analysis

Table 1 summarises the financial metrics computed for each renewable scenario against the fossil-fuel baseline at a 5% discount rate over 10 years.

Table 1. Financial metrics comparison for all energy supply scenarios.

Scenario	CAPEX (€)	OPEX/year (€)	NPV – Net Present Value 10yr (€)	ROI – return on investment
Scenario 0 – 100% ICE Generator	2,221	~36,000+	– (Baseline)	–
Scenario 1 – 100% Solar PV (10P / 8B)	14,095	160.00	315,415	29.64



Scenario 2 – Hybrid Solar-Wind (8P / 6B / VAWT)	12,328	120.00	337,406	34.07
Scenario 3 – Solar PV + ICE Backup (8P / 6B)	13,351	~1,934–2,384	320,932	29.87

Note: P = PV panels; B = Pylontech US5000 batteries; VAWT = Vertical Axis Wind Turbine. Bold row indicates optimal configuration. All NPV calculations use a 5% discount rate over 10 years.

4. Discussion

The results confirm that the hybrid photovoltaic-wind configuration achieves total year-round energy self-sufficiency with the lowest CAPEX (€12,328), the highest NPV (€337,406), and the shortest payback period (0.323 years, approximately 4 months) among all evaluated alternatives. These findings are consistent with the broader literature on hybrid off-grid micro-grids, which identifies complementarity between solar and wind seasonal profiles as the primary driver of storage downsizing and CAPEX reduction.

A particularly significant finding concerns the characterisation of the local wind resource. The initial steady-state assessment – revealing a mean annual velocity of just 1.12 m/s – would conventionally lead to the complete rejection of wind energy as a viable component. However, the transient gust analysis reveals that restricting the evaluation to continuous averages introduces a systematic assessment error in turbulent mountain environments. The localised winter gusts, reaching 73.4 km/h, are precisely temporally aligned with periods of solar generation deficit, making even brief exploitation events sufficient to resolve multi-day energy shortfalls. This suggests that in mountainous off-grid contexts, conventional wind feasibility thresholds designed for uniform laminar flow conditions may underestimate the available resource. Future research using higher-frequency anemometric logging (sub-hourly) and VAWT dynamic power-curve modelling could more accurately quantify the energy harvested from transient events.

The rejection of geothermal exploitation (Module C) deserves further contextualisation. The site presented technically adequate subsoil thermal conditions ($T_g \approx 16^\circ\text{C} \pm 1^\circ\text{C}$ at shallow depth), theoretically capable of supporting a Ground-Source Heat Pump. However, the physical constraints – consolidated fractured limestone requiring diamond-tipped percussion drilling and the impossibility of transiting heavy machinery via the mountain access roads – rendered both vertical and horizontal configurations economically unviable. This finding highlights an often-overlooked constraint in off-grid geothermal studies: the logistical accessibility threshold may be a more binding constraint than the geological or thermal one, particularly in remote terrain.

The comparison between Scenarios 1 and 2 reveals the cost efficiency of strategic storage downsizing enabled by wind hybridisation. Scenario 1 required two additional battery units (38.4 vs 28.8 kWh) and two additional PV panels (5.35 vs 4.28 kWp) solely to address the January deficit, adding approximately €1,767 in CAPEX and eliminating the need for wind integration. Scenario 2 achieves a superior financial outcome by investing €1,198 in the VAWT, thereby resolving multiple winter deficit months simultaneously. This demonstrates that in systems with highly seasonal complementarity, infrastructure diversification represents a more capital-efficient strategy than component over-dimensioning.

Scenario 3 illustrates that introducing even minimal residual fossil-fuel dependency substantially erodes the long-term financial performance. Despite operating the generator for only 11 days per year, the 4% annual fuel cost escalation and mandatory maintenance create a compounding OPEX drain, reducing the 10-year NPV to €320,932 – €16,474 below Scenario 2. This differential will continue to widen as carbon pricing mechanisms under the European Green Deal progressively increase fuel costs (Abasova, Zaidi, & Ashraf, 2026).

Several limitations of this study must be acknowledged. First, the wind energy yield from transient gusts is estimated using a static power curve approach applied to recorded peak values, which provides a conservative lower bound but does not capture the full temporal distribution of sub-peak gust events throughout each day. A continuous power integration using high-resolution meteorological time series would improve accuracy. Second, the PVGIS-SARAH3 climate database (EC–



JRC, n.d.) exhibits inherent year-to-year variability (standard deviations of 6.5-25.7 kWh/month), which was accounted for in the Worst Month design criterion but not propagated through a probabilistic reliability analysis. Third, the financial model does not include the potential residual value of components at the end of the 10-year evaluation horizon, nor does it account for battery replacement cycles beyond 10 years, which could alter the absolute NPV values while preserving the relative ranking of scenarios (for instance, for Scenario 2, please see Figure 5):

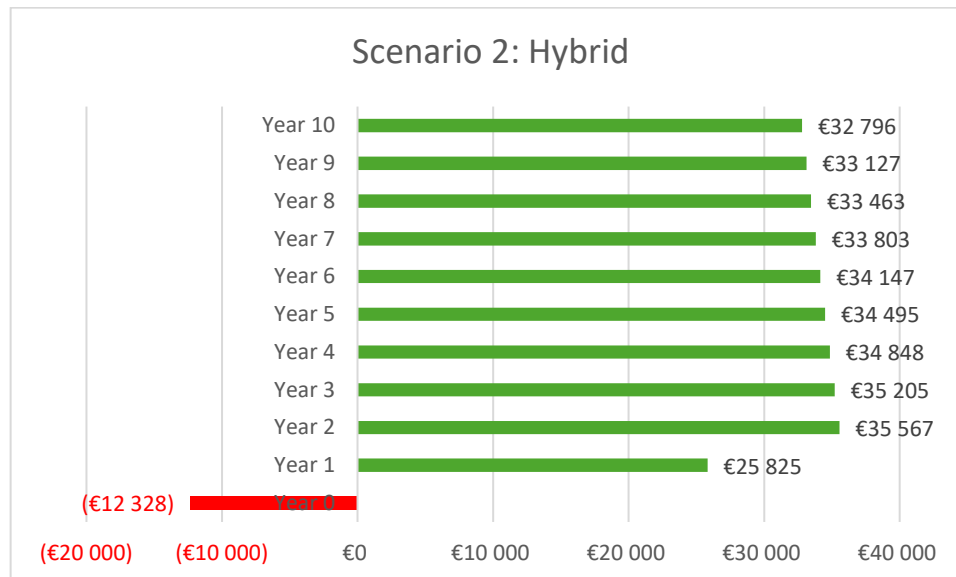


Figure 5. 10-year discounted savings and financial metrics - Scenario 2

5. Conclusions

This study successfully developed and validated a replicable modular engineering framework for the design, resource filtering, and financial benchmarking of off-grid hybrid renewable energy systems in isolated rural Mediterranean environments. Applied to a permanent residential property in El Pla de La Llacuna (Villalonga, Valencia, Spain), the methodology demonstrated the following.

- (1) A hybrid solar-wind architecture (8 × 535 Wp PV + 28.8 kWh LiFePO₄ + 10 kW VAWT) achieves complete annual self-sufficiency with the most competitive technical and financial performance: CAPEX of €12,328, OPEX of €120/year, NPV – Net Present Value of €337,406, ROI – Return On Investment of 34.07, and a payback period of 0.323 years.
- (2) The modular filtering process formally rejected geothermal exploitation due to logistical inaccessibility and geological drilling constraints. It rejected continuous wind generation due to sub-threshold mean velocities, while approving it as a transient support asset based on intense seasonal gust activity.
- (3) The 100% fossil-fuel baseline accumulated €433,570 over 10 years, demonstrating the economic infeasibility of continued fossil fuel dependence in the context of rising fuel costs and carbon pricing.

The modular catalogue framework constitutes a transferable blueprint applicable to other isolated rural dwellings across Mediterranean mountainous regions. Three primary avenues for future research are identified: (i) continuous empirical data logging of the physical installation to validate and refine the computational sizing coefficients; (ii) evaluation of the additional capacity requirements arising from Electric Vehicle integration as rural electrification shifts toward e-mobility; and (iii) extension of the single-household methodology to Renewable Energy Community (REC) scale, assessing the technical and economic feasibility of interconnecting multiple off-grid properties across the La Llacuna plateau into a shared decentralised smart micro-grid.



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Sustainability comparison of petrol and electric small boats on Lake Balaton: A life cycle and total cost analysis

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Abstract

Because Lake Balaton is shallow and ecologically fragile, the regulation of small-boat traffic on the lake currently rests mainly on propulsion type: recreational use of internal-combustion-powered small boats is effectively prohibited. In contrast, purely electric-powered boats may operate freely. This study examines the environmental and economic differences between petrol and electric-powered small boats over their full life cycle, and considers what these differences imply for further developing the regulatory framework. The analysis draws on data from one specific petrol-powered and one electric small-boat model. The life cycle assessment (LCA) compares CO₂ emissions across the manufacturing, operational, and end-of-life (EoL) phases over 15-year and 20-year horizons, while the total cost of ownership (TCO) analysis compares investment, operating, mooring, and maintenance costs over the same horizons. Results: manufacturing emissions for the electric boat are nearly five times those of the petrol boat, but this disadvantage is offset by lower operating emissions within roughly 5.7 years; over 15 years, the electric boat's total emissions are about half those of the petrol boat. The economic picture runs in the opposite direction: owing to its higher purchase price and the cost of battery replacement, the electric boat's total cost exceeds the petrol boat's over both examined time horizons. Since environmental and economic considerations do not align, sustainable boating cannot be reduced to a single criterion and instead calls for deliberate, multi-criteria evaluation. Regulation would benefit from accounting not only for propulsion type but also for the actual environmental burden a boat generates (speed, power, intensity of use).

Keywords

leisure boating, life cycle assessment, total cost of ownership, Lake Balaton, sustainability

1 Introduction

Sustainability plays an increasingly decisive role in the evolution of transport systems today, particularly in settings where environmental impact directly affects ecosystem health. Waterborne transport, specifically small-boat traffic, takes on particular significance when it occurs in a sensitive environment such as Lake Balaton. Balaton is Hungary's largest standing body of water, at once a national natural asset and a central pillar of domestic tourism, so its use requires a continuous balancing act between economic interests and environmental protection. Because the lake is shallow, with an average depth of just 3.3 meters (OVF, n.d.), and largely enclosed, the environmental pressures created by boat traffic – air pollution (Viana



et al., 2014), fuel and oil contamination (Depree, 2007; Jüttner et al., 1995), noise, wave generation, and sediment resuspension – take hold quickly and intensely (Carreño and Lloret, 2021; Mosisch and Arthington, 2004).

Accordingly, recreational use of internal-combustion-powered small boats on Lake Balaton is, as a general rule, prohibited, with only a narrow set of exceptions – for example, sailboats' auxiliary engines during calm winds, or vessels performing official or public-service duties (Government Decree 30/2003 (III. 18.); NFM Decree 57/2011 (XI. 22.)). Purely electric-powered boats, by contrast, may operate freely, since their use produces no local exhaust emissions, generates less noise, and carries no risk of fuel leakage. This regulatory logic essentially treats propulsion type as the main decision criterion, even though the full environmental impact of electric boats can only be understood by considering the entire life cycle: battery manufacturing, the composition of the electricity used to charge them, and end-of-life treatment.

Choosing a propulsion system is therefore a decision-theoretic problem as well: boat owners and regulators alike must weigh a combination of information – life-cycle emissions, total cost, and the regulatory framework – whose interpretation and integration constitute a cognitive task. This connects directly to the concept of cognitive sustainability, which draws on cognitive science to describe and model sustainability, linking its ecological, economic, and social dimensions within a single holistic framework (Zöldy et al., 2022). The economic dimension of this concept focuses on how individuals or organisations can make conscious, resource-allocation decisions that account for all relevant factors – precisely the problem the present study addresses by jointly applying life cycle assessment and total cost of ownership analysis. Waterborne transport also features within the cognitive mobility (CogMob) framework: the digitalisation of port infrastructure and data-driven support for propulsion-related decisions are increasingly linking human and machine cognitive capacities within mobility systems (Zöldy and Baranyi, 2023). Energy management in boating – whether estimating fuel consumption or designing battery-electric propulsion – offers a concrete example of how sustainability enters the decision matrix (Zalacko et al., 2020), while waste-based and alternative fuels, along with the circular economy, are gaining growing importance in the end-of-life treatment of vessels (Zsoldos et al., 2025).

The present study examines the environmental and economic differences between petrol- and electric-powered small boats and how these differences can be interpreted in the specific environmental and regulatory context of Lake Balaton. The analysis rests on two pillars: a life cycle assessment (LCA), evaluating CO₂ emissions generated over the boats' full life cycle, and a total cost of ownership (TCO) analysis, examining economic considerations over a longer time horizon. Our starting point is that environmental and economic considerations do not necessarily lead to the same conclusions. The aim is to show what trade-offs arise when these considerations are weighed together.

2 Data and methods

2.1 Regulation at Lake Balaton and internationally

Under NFM Decree 57/2011 (XI. 22.) on the rules of waterborne transport, a small boat is defined as any self-propelled, motorised vessel with a hull shorter than 20 meters and a maximum carrying capacity of 12 people. On Lake Balaton, recreational operation of such boats with internal combustion engines is prohibited – apart from the narrow exceptions set out in Government Decree 30/2003 (III. 18.) – while purely electric boats are permitted, subject to strict technical conditions that rule out hybrid or auxiliary-engine solutions. An international perspective nuances this either/or regulatory logic. At Lake Garda in Italy, speed limits (20 knots by day, 5 knots at night) serve as the main instrument. The lake's northern, more ecologically sensitive basin – largely within the province of Trento – has its own zone strictly restricting motorised boating (Boat Garda, n.d.). Water quality at Lake Garda is also studied intensively (Giardino et al., 2007), underscoring the need to combine regulation with monitoring for sensitive large lakes. At Lake Constance (Bodensee), one of Europe's most important sources of drinking water, regulation centres on engine-emissions compliance: boats fitted with engines meeting EU directives are exempt from individual testing, while power limits (59 kW for outboard motors, 150 kW for inboard motors) and near-shore speed restrictions complete the system (Boote-Magazin, 2016). Both examples show that, between outright prohibition and unrestricted access, a range of intermediate solutions based on speed, power, and zoning exists – solutions that could inform refinements to Balaton's regulatory framework. Adopting them unchanged would nonetheless be unwarranted, given that Balaton's shallowness, tourism role, and conservation significance together create a distinctive situation.

2.2 Life-cycle assessment methodology



Using the Life Cycle Assessment (LCA) method, this study compares the CO₂ emissions generated over the full life span of one petrol-powered and one electric small-boat model, split into three phases: manufacturing, operation, and end-of-life (EoL) treatment. In the manufacturing phase, the mass of each system (hull, propulsion, fuel system/battery) was combined with the specific manufacturing energy demand of the relevant materials (MJ/kg), which was then converted into CO₂ equivalents using the average emission intensity of the European Union's electricity mix (253 g CO₂/kWh, i.e. roughly 0.07 kg CO₂/MJ) (Ember, 2022). In the operational phase, the petrol boat's emissions were based on manufacturer-reported fuel-consumption figures (19.5 l/h at a 40 km/h cruising speed; 1.9 l/h at idle) together with an internationally used emission factor of 2 310 g CO₂/liter, while the electric boat's emissions relied on the specific emission intensity of the Hungarian electricity mix, 274.9 g CO₂/kWh (MVM Next, n.d.). In the end-of-life phase, each boat's final CO₂ balance was calculated from the emissions and savings associated with the recycling, incineration, and landfill shares assigned to each material fraction (metal, composite, lithium-ion battery). Calculations were carried out for 15- and 20-year service lives, complemented by a sensitivity analysis assuming an average speed of 50 km/h and a further analysis excluding the hull's life cycle. This methodology is consistent with LCA frameworks previously applied to compare propulsion systems in the maritime sector (Bordbar et al., 2025; Jeong et al., 2018), which likewise emphasise that battery manufacturing represents a substantial burden concentrated in the early stages of the overall life cycle (Ellingsen et al., 2014).

2.3 Total cost of ownership methodology

The total cost of ownership (TCO) analysis aggregates investment (purchase price), operating (fuel or electricity), mooring and storage, and maintenance costs over 15- and 20-year horizons. In the 20-year scenario, a one-off but substantial cost item – battery replacement – was also built into the model for the electric boat. The purpose of this methodology is to reveal how the various cost components jointly shape the economic assessment of the two boat types, and whether the operating-cost advantage can offset the initial gap in investment cost.

3 Results and discussion

3.1 Life cycle assessment

In the manufacturing phase, the electric boat's emissions (34,322 kg CO₂) are nearly five times those of the petrol boat (7,141 kg CO₂), owing mainly to the energy-intensive production of the aluminium hull and the 400 kg lithium-ion battery. In the operational phase, however, the picture reverses: over 15 years, the petrol boat emits 68,384 kg of CO₂, compared with just 12,370 kg for the electric boat, meaning that fossil-fuel consumption alone exceeds the electric boat's total life-cycle emissions (*Table 1*). The electric boat's advantage widens further in the end-of-life phase: thanks to the high recycling rate of aluminium and other metal components, it achieves a saving of 6,338 kg CO₂, compared with just 294 kg CO₂ for the petrol boat's composite hull.

Table 1. Total life cycle CO₂ emissions over 15- and 20-year horizons (kg CO₂)

Phase	Petrol (15 yr)	Electric (15 yr)	Petrol (20 yr)	Electric (20 yr)
Manufacturing	7 141	34 322	7 141	34 322
Operation	68 384	12 370	91 199	30 992
End-of-life (EoL)	-294	-6 338	-294	-6 338
Total	75 232	40 354	98 047	58 976

** please note negative signs mean CO₂ savings of end-life recycling*

Analysis of the cumulative emissions curves shows that the electric boat's initial manufacturing disadvantage is recouped within 5.66 years, after which its cumulative emissions remain below those of the petrol boat. In the sensitivity analysis, more intensive use (an average speed of 50 km/h) shortens the payback period to 5.11 years, since the petrol boat's fuel consumption rises disproportionately faster with speed than the electric boat's energy consumption does. Excluding the hull's life cycle from the system boundary – as the heaviest and most distorting element – shortens the payback period further, to 4.1 years, confirming that the drivetrain and battery alone compensate quickly for the initial excess in manufacturing emissions.



3.2 Economic results

The total cost of ownership analysis points in the opposite direction to the environmental results. The electric boat's purchase price (HUF 79,7 million) is nearly five times that of the petrol boat (HUF 16,2 million), a gap its lower operating cost cannot offset (HUF 10,1 million over 15 years, compared with HUF 16,7 million in fuel costs for the petrol boat). Mooring and storage fees are identical for both boat types and represent a substantial cost item. As a result, over a 15-year horizon, the petrol boat's total cost is HUF 62,6 million, compared with HUF 118,8 million for the electric boat. In the 20-year scenario, the roughly HUF 8 million cost of battery replacement for the electric boat widens the gap further, to HUF 78,1 million versus HUF 139,9 million (*Table 2*).

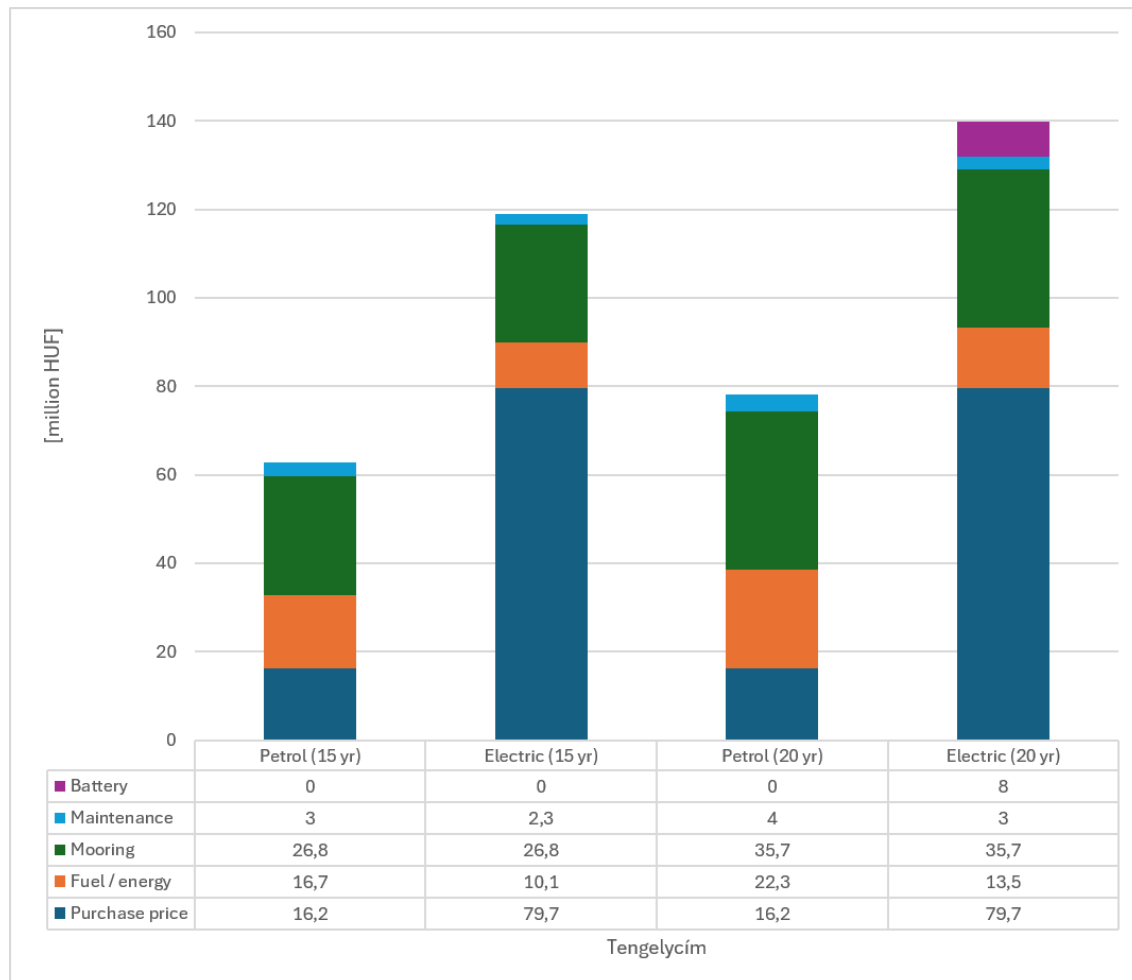


Fig. 2 Total costs over 15- and 20-year horizons (HUF million)

Source: own calculation

3.3 Interpreting environmental and economic considerations together

These results reinforce two, partly conflicting, conclusions. From an environmental standpoint, electric propulsion is clearly the more favourable option for Lake Balaton's sensitive ecosystem: the absence of local emissions, lower noise levels, and a favourable end-of-life balance all point in this direction and are consistent with other LCA studies of boating (Bordbar et al., 2025). Economically, however, the petrol boat remains the cheaper option under current conditions, since the burden of the electric boat's high purchase price and battery replacement outweighs the savings generated by lower operating costs. This discrepancy illustrates well that, in practice, sustainability decisions cannot be reduced to a single indicator. Boat owners and regulators alike need to weigh environmental and economic information together deliberately to



reach a well-founded decision. This kind of multi-criteria, data-driven evaluation lies at the very heart of the concept of cognitive sustainability (Zöldy et al., 2022).

The current Balaton regulation, which treats propulsion type as the main dividing line, is defensible on environmental grounds, yet it does not differentiate boats by their actual environmental burden. While an electric boat produces no local exhaust emissions, the physical burden created by wave action, speed, and power – sediment resuspension, disturbance of shoreline habitats – remains present regardless (Gabel et al., 2017; Kunc et al., 2016), particularly in a lake as shallow and eutrophication-prone as Balaton (Istvánovics et al., 2007; Csősz, 2021). Past fish-kill events at Balaton likewise show that the lake reacts sensitively to human-induced pressures (Takács et al., 2013). In light of this, the future direction of regulation may lie not in relaxing restrictions but in refining them: a differentiated approach based on speed and power, one that accounts for the differing sensitivities of specific areas of the lake, could play a larger role. Building such a system, grounded in actual burden rather than propulsion type alone – in line with the data-driven, digitalisation-oriented approach of cognitive mobility (Zöldy and Baranyi, 2023) – would require more precise data on the spatial and temporal patterns of boat traffic. In designing incentives to ease the economic constraints of switching technologies (e.g. targeted subsidies, fee discounts), it is also worth bearing in mind that not every electric boat delivers the same degree of environmental benefit, and that battery-related costs and emissions (Ellingsen et al., 2014; Zsoldos et al., 2025) are expected to become more favourable in the medium term as the technology continues to mature.

4 Conclusion

This study examined the environmental and economic dimensions of small-boat navigation on Lake Balaton, with particular attention to the roles of petrol and electric propulsion. According to the life cycle assessment, the electric boat's higher manufacturing emissions are offset within 5–6 years by its lower operating emissions and more favourable end-of-life balance, yielding substantial CO₂ savings over the longer term. The total cost of ownership analysis, by contrast, shows that under current conditions the petrol boat can be operated at a lower total cost, since its operating-cost savings cannot offset the burden of a higher investment cost and battery replacement. The tension between these two perspectives points to the fact that sustainable boating is not a simple matter of technology choice but a decision problem that is, in its own right, cognitively complex, requiring the joint weighing of environmental, economic, and regulatory factors.

Limitations of this study include its reliance on data from a single petrol- and a single electric-boat model, as well as the fact that battery costs and the emission intensity of the electricity mix are both parameters that shift over time. Future work should therefore refine the analysis by drawing on a broader fleet of boats, longer time series of price and emissions data, and actual boat-traffic data from Lake Balaton, and should examine the practical feasibility of introducing a differentiated regulatory model based on power and speed.

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Is the electric car really greener and cheaper? A coupled life cycle and total cost of ownership analysis of a petrol and an electric Volkswagen Golf in the Hungarian context

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Abstract

Electric cars are increasingly popular on the assumption that they have a low environmental impact. Yet, battery production is an exceptionally polluting process, and their higher purchase price calls into question their economic competitiveness. Hence, the electric car is not a perfect alternative to internal combustion engine (ICE) vehicles; it requires context-specific investigation. This study couples a Life Cycle Assessment (LCA) and a Total Cost of Ownership (TCO) analysis of two near-identical vehicles. A petrol Volkswagen Golf 1.5 TSi and an electric e-Golf (both 2019), plus a solar-charged variant of the latter, from production to 200,000 km, using a transparent, openly shared model parameterised for Hungary. The Golf's production emissions are 44% of the e-Golf's, but over 200,000 km, the Golf emits 103% more CO₂-equivalent than the grid-charged e-Golf and 222% more than the solar-charged one, reaching environmental break-even after approximately 38,000 and 30,000 km. Economically, the Golf is 10% and 28% more expensive to own, with financial break-even occurring after approximately 62,000 and 66,000 km, respectively. Only 16.7% of the money spent on petrol, against 70.4% for electricity, is converted into useful motion. Mass adoption of electric cars is thus an environmentally optimal direction,



maximised by renewable charging, but it leaves open questions about public revenue sustainability that deserve further investigation.

Keywords

electric vehicle; life-cycle assessment; total cost of ownership; sustainable mobility; CO₂ emissions; solar charging; Hungary

1. Introduction

Sustainable societal operations and environmental protection are among the most pressing topics of our time, and the burning issue of global warming, driven by the combustion of fossil fuels, is one of its most decisive components (Robinson & Igini, 2025). Road transport is a major contributor: in the European Union in 2022, transport accounted for 31% of all energy use, of which road transport was responsible for the largest share, 73.6%, and within that, petrol/diesel-powered vehicles accounted for 65.4% (Eurostat, 2024). At the global level, transport was responsible for roughly 24% of CO₂ emissions, with the road sector accounting for 74.5%, split between 45.1% private use and 29.4% freight (Richie, 2018). These figures show that road transport plays a decisive role in greenhouse gas (GHG) emissions and that the type of vehicle drivetrain is central to mitigating them.

The electric car family is one of the alternatives developed to address this environmental burden. A battery electric vehicle (BEV) is propelled exclusively by one or more electric motors and has no secondary drivetrain. Its most significant distinguishing feature from Internal Combustion engine (ICE) vehicles is that no pollutants leave the motor as by-products during use (European Commission, n.d.). The momentum behind the technology is considerable: according to the International Energy Agency (IEA), 20% of cars sold globally in 2024 were electric – about 17 million vehicles, compared with only 500,000 in 2016 (IEA, 2025). Electric drivetrains also use energy far more efficiently: an electric motor converts on average about 70% of the stored energy into motion, rising above 90% when regenerative braking is included, whereas an ICE converts only around 30%, the remaining 70% being lost mainly as heat (U.S. Department of Energy, n.d.; Cushman-Roisin and Cremonini, 2021).

Despite these advantages, the electric car is not a perfect, so-called “zero-emission” alternative. Battery production is an outstandingly polluting process: the estimated manufacturing CO₂ emissions of a lithium-ion battery span a wide range, from 55 to 494 kg CO₂-eq per kWh, reflecting big regional differences in mining, processing, and the resources used in assembly (Hall and Lutsey, 2018; Schnell et al., 2025). Moreover, the mining of battery raw materials has impacts that cannot be offset by emissions accounting alone, such as water scarcity caused by intensive lithium production in Chile, Argentina, and Bolivia (Tilly et al., 2024). Two questions therefore arise and motivate this work: would mass electrification genuinely reduce CO₂ emissions, or would additional pollution appear elsewhere in the life cycle of the electric car, and how would such a shift hold its ground economically?

Existing literature has examined these questions separately. Lifecycle comparisons of ICE and electric vehicles exist for various regions (Farzaneh and Jung, 2023; Hall and Lutsey, 2018): Total-cost-of-ownership analyses – including recent work focused on Hungary across affordable, mid-range and premium market segments (Zoldy, 2026a; Zsiborács et al., 2026; Ouyang et al., 2021) – have assessed economic competitiveness. Less common is an integrated, region-specific assessment that couples the environmental and economic accounts for a single, controlled vehicle pair and isolates the effect of the drivetrain rather than vehicle design. The present study addresses this gap.

Beyond the technical and economic dimensions, the transition toward electric mobility is also a cognitive one: individuals must reconcile environmental, financial, and practical considerations that are often perceived as conflicting, under conditions of incomplete or asymmetric information. Lerchner and Zoldy (2026a) show that individual car-purchasing decisions rarely align with the environmental preferences that buyers themselves report, pointing to a persistent gap between stated environmental values and realised purchasing behaviour. This gap is amplified by the fact that the cost–emission relationship is not static: Lerchner and Zoldy (2026b) demonstrate, in a yearly total CO₂ emission assessment of passenger-car electrification, that the environmental balance of a fleet shifts non-linearly over time as adoption progresses. This means that a single, static comparison can misrepresent the dynamics a buyer or policymaker actually faces. Zoldy (2026b: 1) frames this problem within the emerging cognitive sustainability paradigm. He argues that the total cost of ownership functions not merely as an economic bottom line but as a “cognitively informed decision interface shaped by perception, trust, and



information asymmetry”, and that the relationship between cost and emissions is dynamic and non-linear over time, particularly during electrification, where short-term increases can precede long-term benefits.

The present study addresses this cognitive dimension in a concrete, quantitative manner. By coupling a transparent LCA and TCO model – openly shared rather than presented only as aggregate results – and by explicitly locating the environmental and financial break-even points rather than reporting only endpoint totals, the analysis is designed to function as a decision-support tool that narrows the information asymmetry identified by Zoldy (2026b) and the preference-behaviour gap identified by Lerchner and Zoldy (2026b). In this sense, the coupled LCA–TCO framework proposed here operationalises, for a controlled Hungarian vehicle pair, the integrated perspective on cost structures, decision-making, and emission dynamics that cognitive sustainability research calls for.

It is not our intention to portray ICE vehicles as an entirely bad option, nor the electric drivetrain as a perfect alternative; rather, we quantify, in the Hungarian context, where the electric car becomes “greener” and “cheaper”, and what conditions maximise its potential.

2. Materials and methods

2.1 Vehicle selection and data

To isolate the effect of the drivetrain, we compare the petrol and electric variants of a single manufacturer’s platform: the 2019 Volkswagen Golf 1.5 TSi (hereafter Golf) and the 2019 Volkswagen e-Golf (hereafter e-Golf), the latter is also analysed under solar charging (hereafter e-Golf(S)). The two cars are built on a fully shared platform and share almost every external feature. The manufacturer differentiates them only in minor details such as a brand logo or specific LED integrations (2019 e-Golf Press Kit, 2019). They also have very similar power, 130 PS (≈ 96 kW) for the Golf and 134 PS (≈ 100 kW) for the e-Golf, and the e-Golf is only about 215 kg heavier. These near-identical body properties make the pair an optimal choice, because differences arising from aerodynamic or design factors do not bias the comparison, allowing more general conclusions about the two technologies (ADAC Autokatalog, 2017, 2018). Key technical data are summarised in *Table 1*.

Throughout, consumption and combined CO₂ values are taken from independent test data (ADAC, 2017), (ADAC, 2018) rather than manufacturer figures to reflect real-world behaviour better.

Table 1 Technical data of the analysed vehicles used as the model framework (manufacturer- and test-data-based).

Source: ADAC Autokatalog (2017, 2018).

Parameter	Golf 1.5 TSi	e-Golf
Consumption	6 L/100 km	15.8 kWh/100 km
Combined CO ₂ emission	135 g/km	0 g/km
Power	130 PS (≈ 96 kW)	134 PS (≈ 100 kW)
Mass	1,400 kg	1,615 kg
Battery capacity	–	35.8 kWh

2.2 Common framework

A custom spreadsheet model was built to automate both LCA and TCO calculations and to enable sensitivity testing with varying input data; the model is openly available (see *Data availability*). Both analyses run from production up to a fixed examined distance of 200,000 km. This distance reflects the Hungarian vehicle-lifetime context: in 2025, the mean age of passenger cars in circulation was 16.2 years (KSH, 2026), which, combined with a European annual mileage of about 12,000 km (ACEA, 2025), yields close to 200,000 km over a full life. A battery replacement is modelled once the car exceeds 150,000 km, conservatively earlier than the manufacturer-guaranteed 160,000 km battery lifetime (Volkswagen, 2026).

2.3 Lifecycle assessment model

The LCA accounts for the direct and indirect environmental impacts of manufacturing, fuel/electricity production, and vehicle use (Method Statement LCA, 2024). All emissions are expressed in kg CO₂-equivalent.

Manufacturing. Manufacturing carbon footprints of specific vehicles are generally undisclosed by manufacturers, so estimates are required. We use the figures reported by Buchal, Karl and Sinn (2019), in which a petrol Golf has a manufacturing footprint of 26 g CO₂-eq/km and an e-Golf of 57 g CO₂-eq/km over a 200,000 km lifetime. Converted to absolute terms (Eq. 1):

$$Emission_{manuf} = (g \text{ CO}_2\text{-eq/km}) \times km / 1000 \quad (1)$$



$$Emission_{manuf,Golf} = 26 \times 200,000 / 1000 = 5,200 \text{ kg CO}_2\text{-eq}$$

$$Emission_{manuf,e-Golf} = 57 \times 200,000 / 1000 = 11,400 \text{ kg CO}_2\text{-eq}$$

These values assume primary-production materials only. According to Volkswagen's 2024 reporting, ICE cars contain, on average, 21.3% reused or secondary-recycled parts. Meanwhile, the same value for electric cars is 18.7% (Volkswagen Group, 2024), which are produced with lower energy input. To avoid a logical error of subtracting recycling credit twice – once at end of life and once at manufacturing – the model corrects the manufacturing estimate by the recycled-content share, since the cars are already assembled with a portion of recycled content (Eq. 2):

$$Emission_{corr,manuf} = Emission_{manuf} \times (1 - \text{recycled share}) \quad (2)$$

$$Emission_{corr,manuf,Golf} = 5,200 \times (1 - 0.213) \approx 4,092 \text{ kg CO}_2\text{-eq}$$

$$Emission_{corr,manuf,e-Golf} = 11,400 \times (1 - 0.187) \approx 9,268 \text{ kg CO}_2\text{-eq}$$

The excess of the e-Golf is attributable to battery manufacturing. For its 35.8 kWh battery, we apply a unit footprint of 71 kg CO₂-eq/kWh, the globally weighted average reported by Green NCAP (2024) across Chinese (77 kg CO₂-eq/kWh), U.S. (57 kg CO₂-eq/kWh) and European (50 kg CO₂-eq/kWh) production, giving $35.8 \times 71 \approx 2,542$ kg CO₂-eq for one battery.

Use phase. Use-phase emissions combine direct (tailpipe) and indirect (well-to-tank, WTT) contributions (Eq. 3):

$$E_{use} = (\text{combined CO}_2 \times \text{distance}) + (\text{distance} \times \text{consumption}/100 \times \text{upstream factor}) \quad (3)$$

For petrol, a WTT factor of 17.5 g CO₂-eq/MJ (Prussi et al., 2020) with an energy content of 33.03 MJ/L (SEAI, 2024) gives 0.578 kg CO₂-eq per litre of petrol produced. For electricity, we use the Hungarian grid factor of 0.2194 kg CO₂-eq/kWh, derived from the 2023 national generation of 35,545 GWh and 7.8 Mt CO₂-eq (IEA, 2025); this is below the European average of 0.2559 kg CO₂-eq/kWh (IEA, 2026). For the solar-charged e-Golf(S), use-phase emissions are taken as 0 kg CO₂-eq, assuming the photovoltaic system fully covers the car's electricity demand. Over 200,000 km, these yields use-phase emissions of 33,936 kg (Golf), 6,935 kg (e-Golf, grid), and 0 kg (e-Golf(S)); for both electric variants, a single battery replacement adds 2,542 kg.

Total and break-even. Total lifecycle emissions are the sum of corrected manufacturing, use, and (where applicable) battery-replacement emissions. To locate the environmental break-even – the distance at which the cumulative emissions of two cars become equal – the model expresses each car's emissions as a linear function of distance (Eq. 4), and solves pairwise for the intersection.

$$F = ((Emission_{total} - Emission_{manuf})/\text{km}) \times x + Emission_{manuf} \quad (4)$$

Because every realistic break-even occurs before the 150,000 km battery-replacement step, the battery-free linear functions are used for this calculation, avoiding the discontinuity.

2.4 Total-cost-of-ownership model

The TCO is the comprehensive aggregation of all expenses associated with owning and operating an asset, including the initial purchase cost, use costs, and depreciation (Toyota, n.d.). Methodologically, it mirrors the LCA; costs are computed as a function of distance, but with phase-specific complexity. All purchase costs are expressed in 2019 Hungarian forint (HUF), converted from the cars' euro list prices at the 2019 exchange rate (≈ 325 HUF/EUR), to capture what the buyer actually spent "then and there". Purchase prices were 8,878,048 HUF (€27,285) for the Golf and 10,379,686 HUF (€31,900) for the e-Golf, the latter being about 17% more expensive (Exchange Rates UK, n.d.). A second examined distance basis of 200,000 km over an assumed 12,000 km/year (≈ 17 years) is used for time-dependent costs.

Fuel and electricity. Petrol cost is computed based on distance, consumption, and an inflation-adjusted average price. Because petrol prices over 2019–2025 showed no stable trend in real terms, a nominal increase of 55.3% corresponded to a



1.85% decrease in real value once inflation was removed. The model does not estimate past prices, but starting from the 2019 average, it applies a conservative constant 4% annual inflation (below the measured 7% historical geometric mean and consistent with the Hungarian National Bank (MNB, 2025) 3–4% forecast), yielding an average price of 532.73 HUF/L over the examined period. For the grid-charged e-Golf, the model applies Hungary’s two-tier household electricity tariff: a reduced price of 36 HUF/kWh up to an annual consumption ceiling and a “market” price of 70 HUF/kWh above it (MVM Csoport, n.d. a; n.d. b), allocated by the shares 0.17 (subsidised) and 0.83 (market) implied by an average household’s prior consumption. For the solar-charged e-Golf(S), the electricity cost is zero by construction.

Vehicle tax, battery replacement, solar system and resale. The model includes the Hungarian vehicle tax, which depends only on power and age and so can be standardised (unlike insurance or service costs, which are owner-dependent and therefore excluded). Over the modelled life, this amounts to 457,920 HUF for the Golf, whereas the electric variants are exempt, as battery-electric vehicles paid no Hungarian vehicle tax in the modelled period. Battery replacement is priced at 50,000 HUF/kWh – derived from a market battery price of ~139 USD/kWh and an insurer rule-of-thumb of 50,000–100,000 HUF/kWh including labour costs (Allianz, 2026) – giving $35.8 \times 50,000 = 1,790,000$ HUF ($\approx$ €5,500).

The solar option is sized based on the annual energy demand, with a Photovoltaic Geographical Information System (PVGIS)-based result of 1,150 kWh/kWp/year for optimally placed Hungarian installations (European Commission, 2025). Based on the examined yearly driven distance and energy consumption, the e-Golf’s demand requires a 1.7 kWp system, priced at an inflation-adjusted 440,000 HUF/kWp (from a 2022 market quotation), totalling 748,000 HUF ($\approx$ €2,300).

Resale value is treated as a negative cost (an amount the owner can recover) and estimated by logarithmic regression on listed prices of 2019 vehicles $p = a + b \cdot \ln(\text{km})$, with $R^2 = 0.796$ (Golf) and 0.967 (e-Golf). At 200,000 km, this gives 5,408,003 HUF (Golf) and 4,862,410 HUF (e-Golf/e-Golf(S)). The total end cost is the aggregate cost minus the resale value. The same intersection logic obtains financial break-even points as in the LCA.

2.5 Economic-utility model

To assess how much of the money spent on energy actually moves the car, the model computes the useful-energy fraction of fuel and electricity expenditure, removing per-unit taxes and contributions, dividing by VAT, multiplying by drivetrain efficiency, and dividing by the gross price. For petrol (gross 580 HUF/L; excise 158.8; energy-efficiency contributions 8.25 and 3 HUF/L; VAT 27%; engine efficiency 30%) and for electricity (gross 70 HUF/kWh; excise 0.415; VAT 27%; drivetrain efficiency 90%), the model returns the useful share of each forint spent (NAV, 2025; 2026a; 2026b).

2.6 Sensitivity analysis

Robustness to driving style and climate was tested by varying consumption. A uniform +10% increase was applied to both cars. As a uniform increase is unrealistic given the greater weather sensitivity of electric drivetrains (extreme temperatures can raise BEV energy use by 50–60%; Parker et al., 2025), an asymmetric scenario (Golf +2%, e-Golf +10%) was also examined, for both the emission and the cost outputs.

3. Results

3.1 Lifecycle emissions

Over 200,000 km, total lifecycle emissions were 38,029 kg CO₂-eq for the Golf, 18,744 kg for the grid-charged e-Golf, and 11,810 kg for the solar-charged e-Golf(S). Although the Golf’s corrected manufacturing footprint (4,092 kg CO₂-eq) is only 44% of the e-Golf’s (9,268 kg CO₂-eq) due to its manufacturing “backpack” driven by its battery, its far higher use-phase emissions dominate the full life cycle. The Golf therefore emits 103% more CO₂-equivalent than the grid-charged e-Golf and 222% more than the solar-charged variant over the examined distance (*Figure 1*). Notably, even the solar-charged e-Golf is not “zero-emission”: its 11,810 kg arises from manufacturing and battery replacement, a reminder that indirect and embodied emissions remain even when use-phase emissions vanish.

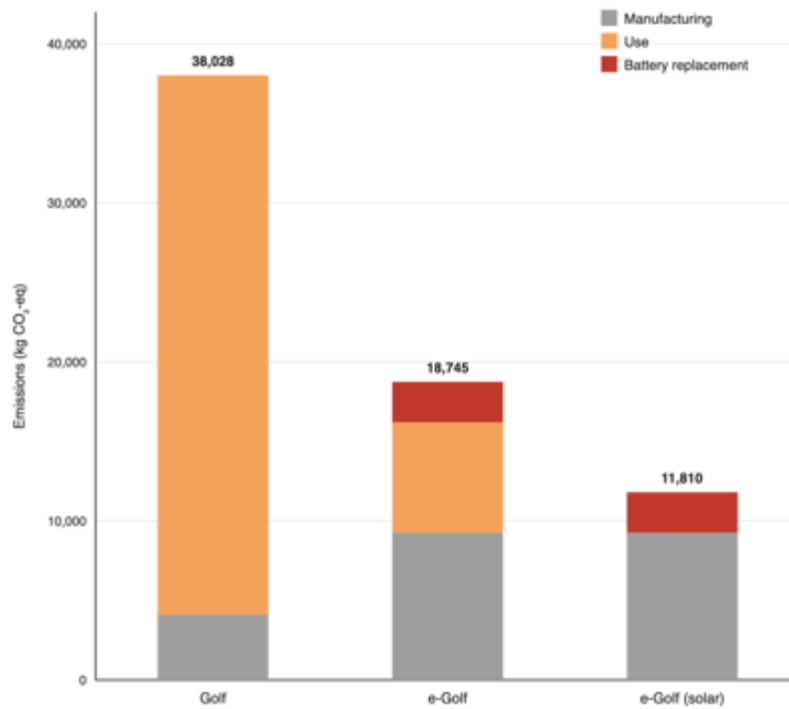


Figure 1. Total lifecycle carbon footprint of the three vehicles over 200,000 km, decomposed into manufacturing, use, and battery-replacement emissions.

Source: own calculation.

The cumulative-emission curves intersect well before the battery-replacement step. So the environmental break-even points (Table 2) were computed on the battery-free linear functions (Figure 2). The e-Golf overtakes the Golf in cumulative emissions at 38,336 km when grid-charged and at 30,305 km when solar-charged. Beyond these distances, each additional kilometre widens the electric car's environmental advantage.

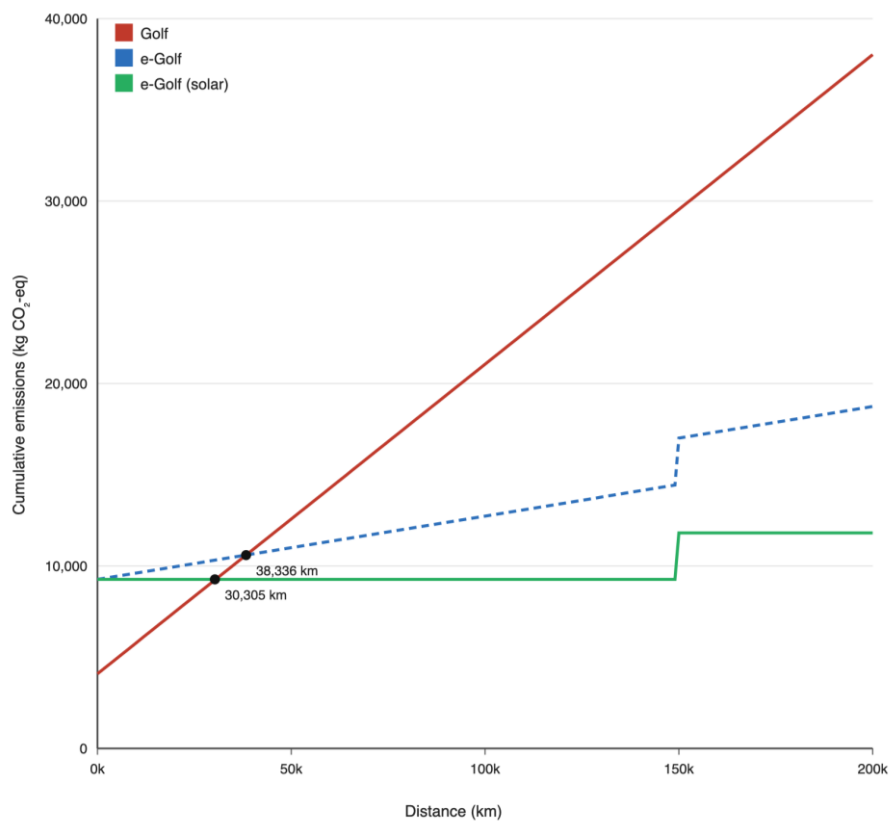


Figure 2. Cumulative lifecycle emissions as a function of distance, with the environmental break-even points marked; the step at 150,000 km reflects battery replacement in the electric variants. *Source: own calculation.*

Table 2. Environmental break-even distances (km). *Source: own calculation.*

Golf / e-Golf	Golf / e-Golf(S)	e-Golf / e-Golf(S)
38,336	30,305	0

3.2 Total cost of ownership

Over 200,000 km, the total end cost was 10,320,717 HUF ($\approx$ €31,700) for the Golf, 9,336,628 HUF ($\approx$ €28,700) for the grid-charged e-Golf, and 8,055,276 HUF ($\approx$ €24,750) for the solar-charged e-Golf(S). Despite its higher purchase price, the e-Golf developed far lower operating costs. 2,029,352 HUF of electricity against 6,392,752 HUF of petrol. So even after a costly battery replacement, the Golf is still 10% more expensive to own than the grid-charged e-Golf, and it is 28% more expensive than the solar-charged variant (Table 3, Figure 3). If the owner does not replace the battery, the gap widens to 37% and 65%, respectively.

Table 3. Total cost of ownership summary over 200,000 km (HUF), including a battery replacement for the electric variants.

End cost = aggregate cost – resale value. *Source: own calculation.*

Vehicle	Purchase	Energy	Tax/battery	Resale	End cost
Golf	8,878,048	6,392,752	457,920	5,408,003	10,320,717
e-Golf	10,379,686	2,029,352	1,790,000	4,862,410	9,336,628
e-Golf(S)	11,127,686	0	1,790,000	4,862,410	8,055,276

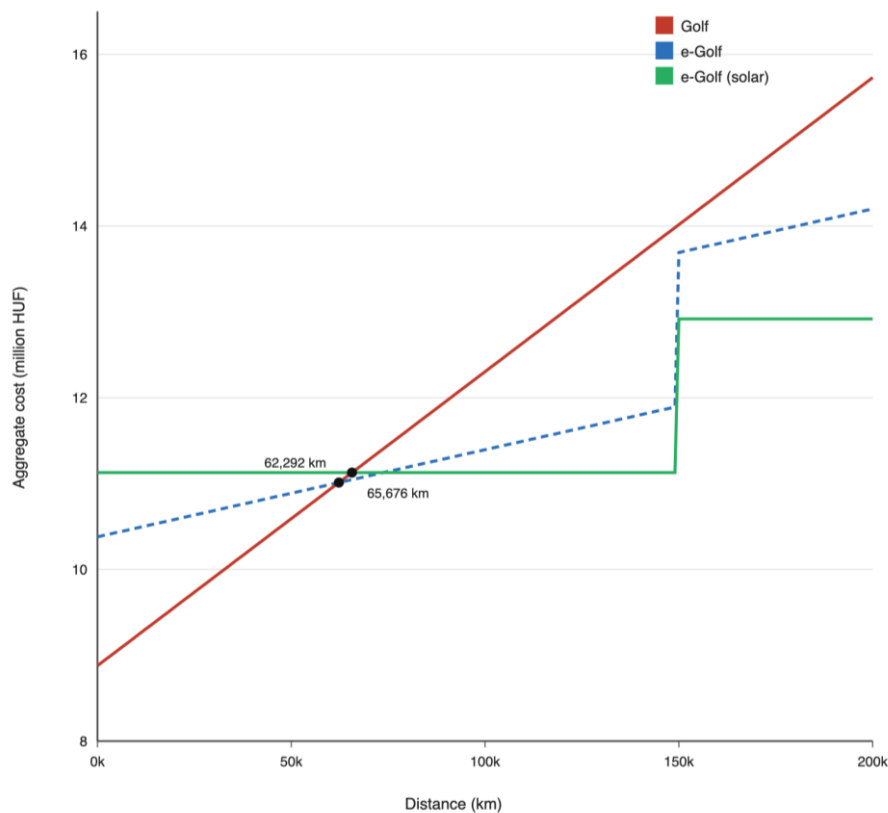


Figure 3. Cumulative ownership cost as a function of distance, with the financial break-even points marked; the step at 150,000 km reflects battery replacement. *Source: own calculation.*

The cost curves cross before the battery-replacement step: financial break-even occurs at 62,292 km (5.19 years) for the Golf/e-Golf comparison, 65,676 km (5.47 years) for Golf/e-Golf(S), and 73,718 km (6.14 years) for e-Golf/e-Golf(S) (Table 4). The owner of an electric car must therefore be patient – the higher initial outlay is recovered over the longer term. But over a full ownership cycle, the electric variant carries the lower cost burden. Moreover, charging it from a solar system makes it the outright cheapest option.

Table 4. Financial break-even distances (km) and the corresponding ownership time at 12,000 km/year. *Source: own calculation.*

	Golf / e-Golf	Golf / e-Golf(S)	e-Golf / e-Golf(S)
Break-even (km)	62,292	65,676	73,718
After (years)	5.19	5.47	6.14

3.3. Economic utility of the energy spent

The fraction of energy expenditure that was useful energy differed sharply between the two technologies. Only 16.7% of the money spent on petrol is converted into useful motion, the remainder being lost to excise (27.4%), VAT (15.0%) and mechanical/thermal losses (39.0%). For electricity, 70.4% of the money spent is converted into useful motion, with much smaller shares lost to VAT (21.1%), mechanical losses (7.8%), and a negligible excise (Figure 4). This difference is driven mainly by the higher drivetrain efficiency of the electric car and by the much lower excise burden on electricity. These percentages (16.7% useful + 27.4% excise + 15.0% VAT + 39.0% mechanical/thermal = 98.1%) don't sum to 100%. The missing ~1.9 percentage points corresponds closely to the 'energy-efficiency contributions' ($8.25 + 3 \text{ HUF/L} \approx 1.9\%$ of the 580 HUF/L gross price) that are included in the Methods 2.5 calculation but not listed here as a separate loss category, unlike the electricity breakdown in the next sentence, which explicitly notes 'a negligible excise' for its own small residual.

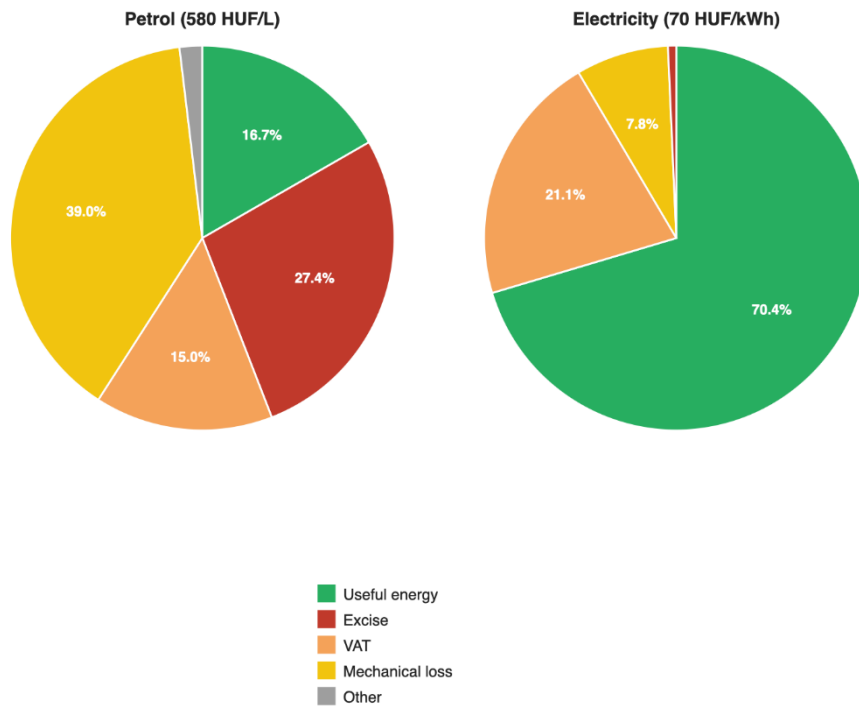


Figure 4. Share of money spent on petrol versus electricity that is converted into useful motion, with the remainder lost to taxes and mechanical/thermal losses. *Source: own calculation.*

3.4 Sensitivity analysis

Emissions and costs scaled predictably with consumption but did not alter the ranking. Under a uniform +10% increase in consumption, the Golf's larger absolute and partly direct emissions caused its total lifecycle footprint to rise more than the e-Golf's, shifting both environmental break-even points slightly "earlier" (in the electric car's favour). Crucially, the e-Golf would have to increase its consumption roughly fivefold to match the additional CO₂ generated by a 10% increase for the Golf; even modelling the e-Golf's consumption growth at five times the Golf's moved its environmental break-even point by only about 21 km, negligible over 200,000 km. On the cost side, a 10% increase in consumption raised the Golf's end cost by 6.19%, but the e-Golf's by only 2.69%, leaving the economic ranking unchanged. The electric car's advantage is thus robust to driving style and colder climates.

4. Discussion

The coupled analysis gives a consistent answer to the two motivating questions for the Hungarian context. Over a realistic 200,000 km life, the electric car is both substantially "greener" and modestly "cheaper" than its petrol twin, and both advantages are maximised by charging from renewable energy. The environmental result is decisive: a 103% to 222% more reduction in emissions, and the economic result, though smaller, is real and favours the user, primarily because of low (partly subsidised) electricity prices and the high efficiency of the electric drivetrain. These findings are consistent with prior lifecycle work (Farzaneh & Jung, 2023; Hall & Lutsey, 2018) and with recent Hungarian total-cost-of-ownership analyses reporting EV competitiveness under domestic energy prices and incentives (Zoldy, 2026a; Zsiborács et al., 2026), while adding a controlled, single-platform, environmentally and economically integrated perspective.

Two caveats temper the optimism. First, the electric car cannot be labelled "zero-emission": even when use-phase emissions are eliminated by solar charging, manufacturing and battery replacement leave a substantial embodied footprint. The result depends on manufacturing estimates – the Buchal, Karl and Sinn (2019) figures have been criticised for, among other things, not crediting expected grid decarbonisation over a vehicle's life. Second, the mining of battery raw materials has impacts that CO₂ accounting does not capture and may be irreversible, such as water depletion linked to lithium extraction in South America (Tilly et al., 2024). The greatest potential, therefore, lies in stronger regulation of raw-material extraction and in charging from renewable sources, which together would shrink both the manufacturing hump and the use-phase footprint.

The economic findings raise a distinct, policy-relevant concern specific to public finance. The same features that make electricity cheap and efficient for the driver – namely low excise and low public contributions –, mean that an electric-car



owner contributes far less to public goods than the owner of an ICE vehicle, whose fuel price is heavily taxed. Because household electricity cannot be separated by end use, it is difficult to tax the electricity used for charging without also taxing, say, a washing machine. If an increasing share of drivers switches from ICE to electric vehicles under non-repayable state subsidies, the revenue available for road maintenance is likely to fall. Sustaining mass adoption, in countries and regions where governments have an environmental interest in promoting through incentives, requires a mature charging infrastructure in which users can place their trust (Guo et al., 2018; Gupta et al., 2021; Sierzechula et al., 2014). It will therefore require a new mechanism through which electric-car owners also contribute to public goods.

Several limitations should be kept in mind. The analysis rests on a single, near-identical model pair; while this design isolates the drivetrain, the emission and cost ratios are broadly representative. The absolute values are specific to these vehicles and to Hungary. The manufacturing emissions rely on a single, debated source, and the recycled-content correction is a transparent but non-standard simplification. Solar charging is idealised as fully covering demand and as carrying zero use-phase emissions, excluding the embodied emissions of the photovoltaic system. The cost model assumes a stable 4% inflation rate with no economic turbulence, excludes owner-dependent insurance and service costs, and assumes the same driver and route for both cars. These constraints narrow the number of exactly modelled cases but do not overturn the relative results, whose ratios reasonably represent the relationship between electric and ICE passenger cars.

5. Conclusions

Coupling a lifecycle and a total-cost-of-ownership analysis on a controlled petrol/electric vehicle pair shows, for the Hungarian context, that mass adoption of electric cars is an environmentally optimal direction. Over 200,000 km, the petrol Golf emits 103% more CO₂-equivalent than a grid-charged e-Golf and 222% more than a solar-charged one, reaching environmental break-even after only about 38,000 and 30,000 km. The electric car is also the lower-cost choice over a full ownership cycle, 10% to 28% cheaper than its petrol twin, with the solar-charged variant the cheapest of all, and with 70.4% of energy expenditure converted into useful motion versus 16.7%. The greatest potential is unlocked by charging from renewable energy, which simultaneously minimises emissions and operating costs. However, the same low energy taxation that benefits the driver implies that electric-car owners contribute little to public goods. So the central open question raised by these results is whether, and through what mechanism, the government can sustain public-revenue contributions as the fleet electrifies. Future work should generalise the analysis beyond a single model pair and quantify the fiscal instruments that can resolve this tension.

Data availability

The full LCA and TCO spreadsheet model, with all input parameters and equations, is openly available at: <https://docs.google.com/spreadsheets/d/1DRdjkeZzqt0dpeKhH2rSj8XbvILozpGs37Zg1Jh55as/edit?gid=1566974654#gid=1566974654>

Declaration of generative AI use

Generative AI was used to speed up translation from the Hungarian thesis.

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Health economics – a global review and prospection

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Abstract

Health systems are increasingly affected by the convergence of public-health, economic, demographic, technological, and environmental pressures, including non-communicable diseases that account for more than 70% of global deaths and antimicrobial resistance, which is projected to cause 10 million annual deaths by 2050, with economic losses comparable to the 2008 financial crisis. This article aims to review health economics as a framework for understanding and improving the allocation of scarce healthcare resources, with emphasis on efficiency, equity, sustainability, and global health-system resilience. Using a narrative global review and prospective policy analysis, the paper synthesizes evidence from international organizations, academic literature, policy reports, and comparative case studies of different healthcare financing models and national systems. The review identifies major theoretical foundations of health economics, including supply and demand, opportunity cost, cost-effectiveness analysis, market failure, information asymmetry, externalities, and the role of government intervention. It also highlights global disparities in healthcare expenditure, universal health coverage, workforce capacity, disease burden, and emergency preparedness. The findings suggest that sustainable health-system reform requires stronger global health governance, equitable financing, expanded universal health coverage, health-workforce investment, improved pharmaceutical access, and responsible integration of digital health and artificial intelligence. The article contributes by connecting health economics with sustainable policy design and by outlining practical directions for more efficient, equitable, and resilient healthcare systems.

Keywords

health economics; universal health coverage; healthcare financing; market failure; global health; sustainable health systems; digital health; artificial intelligence in healthcare; health equity; healthcare policy

1. Introduction

1.1. Global health and economic crises

The contemporary global health landscape is shaped by the convergence of several public-health, economic, demographic, and environmental pressures. Health systems are no longer challenged only by the treatment of disease, but also by the allocation of limited financial, human, technological, and institutional resources in conditions of rising demand. Non-communicable diseases, including cardiovascular diseases, diabetes, cancers, and chronic respiratory illnesses, represent one of the largest long-term pressures on health systems. These diseases account for more than 70% of global deaths and require sustained expenditure for prevention, diagnosis, treatment, and long-term care. At the same time, antimicrobial resistance is projected to cause 10 million annual deaths by 2050, creating economic losses comparable to the 2008 financial crisis (WHO, 2025a; O'Neill, 2016). Also, the COVID-19 pandemic exposed weaknesses in emergency preparedness, supply chains, workforce capacity, and international coordination, showing that health crises can rapidly become macroeconomic crises (Bloom et al., 2018).

These pressures are especially severe in low- and middle-income countries, where health systems frequently operate with limited public financing, shortages of medical personnel, fragile infrastructure, and high dependence on out-of-pocket payments. In many regions of Africa and South-West Asia, infectious diseases, maternal and child mortality, malnutrition, and vaccine-preventable conditions remain major public-health challenges. Sub-Saharan Africa continues to carry a

disproportionate share of global maternal mortality, accounting for approximately 66% of global maternal deaths, while Africa also accounts for around 95% of global malaria cases. Malaria, HIV/AIDS, and tuberculosis remain endemic, and countries affected by political instability and underfunded healthcare systems face additional barriers to service delivery. South-West Asia, including countries such as Afghanistan and Pakistan, faces similar pressures, as political instability and underfunded health systems compound infectious disease, malnutrition, and child mortality risks. In these contexts, approximately 1 in 10 children die before the age of five, mainly because of vaccine-preventable diseases and malnutrition (World Bank, 2023a; WHO, 2023e).

The economic dimension of these crises is visible in the persistent gap between high-income countries and the Global South, a division geographically shown in Figure 1. While high-income countries often spend between 10% and 18% of GDP on healthcare, many low- and middle-income countries allocate less than 5%, creating structural shortages in personnel, medicines, infrastructure, and preventive services (OECD, 2023b; WHO, 2023b). This underfunding contributes to workforce migration, also known as brain drain, as doctors and nurses often move from poorer health systems to wealthier ones, deepening capacity gaps in the countries that need health workers most (International Organization for Migration, 2024). In addition, reliance on out-of-pocket payments exposes households to catastrophic health expenditure and can push vulnerable populations into poverty (WHO, 2023e).

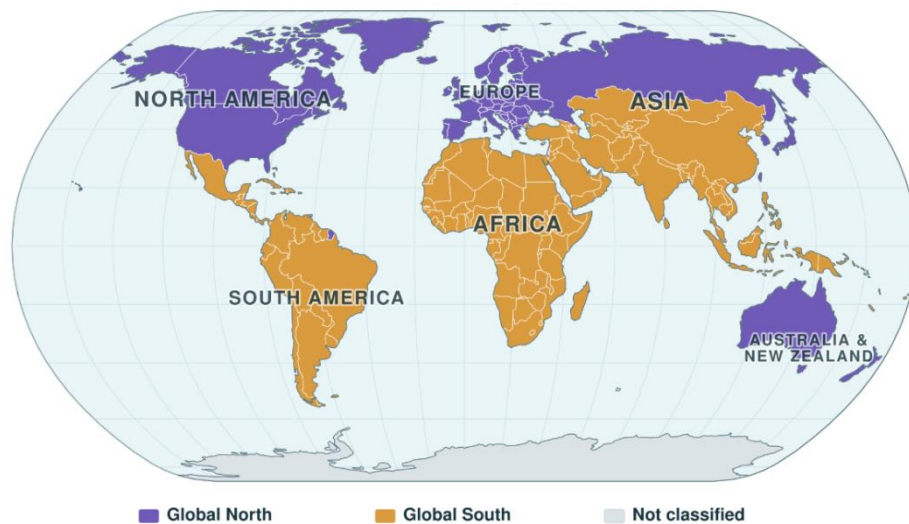


Figure 1 Global North and Global South division
(based on *Encyclopaedia Britannica* (n.d.))

This underfunding produces has concrete consequences for the workforce and for financing. The World Health Organization (WHO, 2023e) estimated a global deficit of 11 million healthcare workers by 2030, while reliance on out-of-pocket payments pushes approximately 100 million people into extreme poverty each year. These figures show why healthcare financing is not only a technical issue, but also a poverty, equity, and development issue.

However, health-economic pressure is not limited to low-income settings. In high-income countries, healthcare can also become a major source of financial insecurity. The United States illustrates how high expenditure does not automatically generate equitable access or efficient outcomes. Despite very high per-capita healthcare spending, estimated at approximately \$12,914 per person and nearly double the OECD average, the country continues to face insurance gaps, high treatment costs, administrative complexity, and medical debt. Around 30 million Americans remain uninsured, and 66.5% of U.S. bankruptcies have been linked to medical expenses, showing how market failures can affect even wealthy health systems (Kaiser Family Foundation, 2026; Himmelstein et al., 2019). These contrasts demonstrate that the central issue is not only how much a country spends on healthcare, but also how resources are financed, distributed, governed, and transformed into health outcomes.

In this context, health economics becomes essential because it provides tools for analysing how scarce resources can be allocated to improve population health efficiently, equitably, and sustainably. The combined pressure of disease burden, underfunding, demographic change, pandemic risk, and unequal access to care shows the need for a systematic economic



approach to healthcare policy. Health economics therefore offers a framework for understanding why health systems fail, how they can be compared, and what types of reforms may improve both health outcomes and economic resilience.

1.2. Definition and scope of health economics

Health economics is a branch of economics that studies how scarce resources are allocated within healthcare systems and how these allocation choices influence health outcomes, efficiency, equity, and financial sustainability. Unlike general market analysis, health economics focuses on a sector in which demand is often urgent, information is unevenly distributed, uncertainty is high, and decisions may affect life expectancy, quality of life, productivity, and social welfare. In this sense, health economics is not limited to the study of healthcare costs, but also examines how health systems are financed, how services are delivered, how policies affect access, and how resources can be distributed in a way that maximizes population health. A useful way to define the scope of health economics is through three core questions: how healthcare should be financed, how healthcare delivery can be made more efficient, and how health policies affect equity and access for marginalized groups. These questions connect financing models, cost-benefit reasoning, and distributive justice within one analytical field.

A central concern of health economics is healthcare financing. Different health systems rely on different combinations of public taxation, social insurance, private insurance, employer contributions, and out-of-pocket payments. Single-payer systems such as Canada's Medicare rely mainly on taxation; social insurance systems such as Germany's combine employer and employee contributions; and out-of-pocket-dominant systems, common in many low- and middle-income countries, place a larger financial burden directly on patients. These financing arrangements strongly influence access to care, risk protection, equity, and the probability that medical expenses will become catastrophic for households (WHO, 2023a).

Health economics also studies efficiency in healthcare delivery. Since health resources are limited, every investment in one intervention implies an opportunity cost, because the same resources cannot be used elsewhere. For this reason, economic evaluation tools such as cost-effectiveness analysis and cost-utility analysis are important in policy decision-making. Cost-effectiveness analysis compares the cost of an intervention with its health benefits, while cost-utility analysis often uses quality-adjusted life years to compare interventions across different disease areas. Concrete examples show the policy relevance of this type of analysis. Vaccination programmes have been estimated to generate approximately \$16 in economic benefits for every \$1 spent, while hypertension treatment can prevent around 10.3 million deaths annually at global level (WHO, 2025a; Sabaté, 2003). These tools help decision-makers evaluate whether resources should be allocated to prevention, diagnosis, treatment, workforce expansion, infrastructure, pharmaceuticals, or public-health campaigns (Folland et al., 2021).

Another major area of health economics is the analysis of behaviour in healthcare. Traditional economic models often assume rational decision-making, but healthcare decisions are influenced by psychological, social, institutional, and informational factors. Patients may delay treatment, fail to adhere to long-term medication, or underestimate future risks. Providers may influence demand through diagnostic and treatment recommendations, and this can create supplier-induced demand when professional authority and financial incentives are misaligned. Patient adherence is another example of why behavioural economics matters for healthcare. Only around 50% of patients with chronic diseases follow long-term treatment plans, meaning that health outcomes depend not only on the availability of medical interventions, but also on patient behaviour, incentives, trust, and system design (Sabaté, 2003). Behavioural economics therefore helps explain why healthcare markets do not always operate according to the assumptions of perfect rationality and why policy design must account for biases, incentives, trust, and institutional context (McGuire, 2012).

The field is also closely connected to equity and public policy. Health economics asks not only whether a health system produces benefits, but also who receives those benefits, who pays for them, and whether vulnerable groups can access essential services. This makes the discipline especially relevant for universal health coverage, because universal coverage requires both access to quality services and protection from financial hardship. As a result, health economics provides a framework for comparing health-system models, identifying market failures, evaluating reforms, and designing policies that improve both efficiency and fairness.

For these reasons, health economics is essential to the study of sustainable health systems. It connects economic reasoning with public-health objectives by analysing how financing, incentives, regulation, and institutional design affect the long-term capacity of health systems to respond to disease burden, demographic change, technological innovation, and future



crises. Its scope therefore includes not only the management of current healthcare expenditure, but also the design of resilient systems capable of producing better health outcomes with limited resources.

1.3. Relevance of health economics for sustainable health systems

Health economics is particularly important because it provides a structured way to examine the inefficiencies that appear at the intersection of healthcare, public finance, social welfare, and institutional governance. Health systems must constantly decide how to allocate limited resources among prevention, diagnosis, treatment, infrastructure, workforce development, pharmaceuticals, emergency preparedness, and long-term care. These decisions are not only technical or medical; they are also economic and ethical, because every allocation choice affects both the quantity of health produced and the distribution of that health across social groups.

One of the central contributions of health economics is its focus on efficiency. In healthcare, inefficiency can appear through unnecessary procedures, duplicated diagnostic tests, avoidable hospitalizations, excessive administrative costs, poorly targeted subsidies, or delayed preventive interventions. Since resources are scarce, inefficient spending reduces the capacity of health systems to respond to other needs. Economic evaluation therefore helps decision-makers compare alternative interventions and identify those that generate the greatest health benefit for the resources available. This is especially important in periods of fiscal pressure, demographic ageing, and increasing chronic disease burden, when health expenditure tends to rise faster than the available public budget (Folland et al., 2021).

A second major contribution is the analysis of equity. Health systems are sustainable only if they protect populations not only from disease, but also from financial exclusion and unequal access to care. A system may be technologically advanced and still fail socially if essential services remain inaccessible to low-income groups, rural communities, migrants, or other vulnerable populations. Health economics therefore examines how financing models, insurance design, co-payments, subsidies, and public provision affect access to care and financial protection. This equity dimension is central to universal health coverage, which requires that people receive needed health services without suffering financial hardship (WHO, 2023a).

Health economics is also necessary because healthcare markets are structurally different from ordinary competitive markets. Patients often lack the same information as providers, demand for urgent care is frequently price-inelastic, and the benefits of some interventions extend beyond the individual patient. Vaccination, antimicrobial stewardship, disease surveillance, and pandemic preparedness all generate collective benefits that markets may underprovide without public coordination. For this reason, government intervention, regulation, public financing, and institutional design are essential parts of health-economic analysis. The classic economic problem of uncertainty in medical care shows why healthcare requires special policy attention and why market mechanisms alone are insufficient to guarantee efficient and equitable outcomes (Arrow, 1963).

Finally, health economics supports policy guidance and long-term resilience. It helps governments and international organizations evaluate which reforms are likely to reduce waste, improve access, strengthen preparedness, and increase the sustainability of healthcare financing. In the context of pandemics, antimicrobial resistance, climate-related health risks, and non-communicable diseases, this policy function becomes increasingly important. Health economics therefore contributes not only to the management of present healthcare expenditure, but also to the design of systems capable of adapting to future shocks while preserving efficiency, equity, and population health.

1.4. Aim, research question, and article structure

Based on these considerations, the aim of this article is to review health economics as a framework for understanding and improving the performance, equity, and sustainability of healthcare systems. The article examines how economic principles can be used to interpret healthcare financing, resource allocation, market failures, public intervention, global inequalities, and the growing pressure created by disease burden, demographic change, technological development, and emergency preparedness needs.

The central research question guiding the article is the following: how can health economics contribute to the development of more efficient, equitable, resilient, and sustainable health systems in different global contexts? This question is addressed through a global review of theoretical concepts, comparative health-system models, major bottlenecks, and policy and technological solutions. The article is therefore not limited to describing healthcare systems, but seeks to connect economic analysis with practical directions for reform.



The contribution of the article is threefold. First, it synthesizes key concepts in health economics, including healthcare financing, cost-effectiveness, opportunity cost, market failure, information asymmetry, externalities, and the role of government intervention. Second, it compares health-system patterns across high-income, middle-income, and low-income countries, showing how financing models and institutional arrangements influence access, efficiency, and outcomes. Third, it identifies major global bottlenecks and discusses possible responses, including universal health coverage, stronger global health governance, health-workforce investment, pharmaceutical access reforms, digital health, artificial intelligence, and sustainable health technologies.

The remainder of the article is structured as follows. Section 2 describes the data and methods used for the narrative review and prospective policy analysis. Section 3 presents and discusses the main findings, including theoretical foundations, global healthcare-system patterns, structural bottlenecks, and proposed policy and technological solutions. Section 4 concludes by summarizing the main arguments, highlighting the significance of health economics for sustainable health-system reform, and identifying limitations and future research directions.

2. Data and methods

This article is designed as a narrative global review and prospective policy analysis of health economics. The purpose of the review is not to test a single econometric hypothesis using primary data, but to synthesize theoretical concepts, comparative evidence, global health-system patterns, and policy-oriented solutions relevant to the sustainability of healthcare systems. The review therefore combines conceptual analysis with comparative interpretation and prospective discussion.

2.1. Review design

The narrative review component is used to organize the main foundations of health economics, including healthcare financing, opportunity cost, cost-effectiveness analysis, market failure, information asymmetry, externalities, government intervention, universal health coverage, and health-system efficiency. These concepts provide the theoretical basis for interpreting why healthcare systems differ in performance and why similar levels of expenditure may produce different outcomes across countries.

The comparative component examines differences between high-income, middle-income, and low-income countries, as well as differences between major healthcare financing models. The article considers tax-funded systems, social insurance systems, private-insurance arrangements, and out-of-pocket-dominant models in order to show how financing structures influence access, equity, financial protection, and system efficiency. This comparative perspective is necessary because health economics is strongly shaped by national income, institutional capacity, political priorities, demographic structure, and public-health needs.

The prospective policy-analysis component identifies major bottlenecks and possible reform directions. These include non-communicable diseases, inefficient healthcare spending, limitations of economic modelling in low-income settings, social determinants of health, emergency preparedness, climate-related health risks, pharmaceutical access, workforce shortages, digital health, artificial intelligence, and sustainable health technologies. The article uses these themes to discuss how health economics can contribute to more efficient, equitable, resilient, and sustainable healthcare systems.

Overall, the research design follows a synthesis logic: first, it defines the conceptual foundations of health economics; second, it compares global health-system patterns; third, it identifies major structural bottlenecks; and fourth, it discusses policy and technological solutions. This structure allows the article to connect theory, empirical comparison, and future-oriented policy recommendations within a single health-economic framework.

2.2. Source base and selection logic

The article is based on secondary sources selected for their relevance to global health economics, healthcare financing, health-system performance, disease burden, equity, and sustainability. The source base includes reports from international organizations, policy institutions, public-health agencies, and academic publications. This approach is appropriate for a global review because health economics depends on comparative data and institutional evidence that are often produced by organizations with international monitoring capacity.

International organizations were used as the main source for global and regional health-system indicators. Reports and databases from the World Health Organization (WHO), the World Bank, the OECD, the United Nations, and the Institute for Health Metrics and Evaluation were used to frame differences in health expenditure, universal health coverage, workforce capacity, disease burden, non-communicable diseases, poverty, and sustainable development (WHO, 2025b; 2023a; World



Bank, 2023a–d; OECD, 2023a–b; IHME, 2023; United Nations, 2023). These sources were prioritized because they provide comparable international indicators and are commonly used in policy-oriented health-economic analysis.

Policy and health-system reports were used to examine specific institutional problems and national cases. For example, sources such as the Kaiser Family Foundation (2026) and the Commonwealth Fund (2024) were used to analyse the United States healthcare system, including insurance coverage, cost pressure, access gaps, and comparative system performance. Similarly, sources connected to the Global Fund (2023), the Global Financing Facility (n.d.), and universal health coverage initiatives were used to discuss health financing, donor-supported programmes, and international policy mechanisms in low- and middle-income countries.

Academic literature was used to support the theoretical and conceptual foundations of health economics. Core economic concepts such as uncertainty in medical care, information asymmetry, physician agency, insurance design, adverse selection, and cost-effectiveness were interpreted through established academic sources in health economics and public-health policy (Arrow, 1963; Folland et al., 2021; McGuire, 2012). These sources are necessary because the article does not only describe health systems, but also explains why healthcare markets differ from ordinary markets and why public intervention is often required.

The selection logic followed three criteria. First, sources were included when they directly supported one of the article's main analytical dimensions: financing, efficiency, equity, disease burden, preparedness, technology, or sustainability. Second, sources were prioritized when they offered internationally comparable data or widely recognized theoretical contributions. Third, case-specific sources were used when they illustrated a broader health-economic mechanism, such as market failure, universal health coverage, workforce shortages, pharmaceutical access barriers, or the role of digital health. This selection logic allows the article to combine global comparability with concrete examples of how health-economic challenges appear in different institutional contexts.

2.3. Analytical framework

The analysis is organized around a multidimensional health-economic framework that connects theoretical concepts, health-system structures, global bottlenecks, and possible reform directions. This framework was designed to make the review coherent across different countries, income groups, financing models, and policy challenges. Instead of treating each country or topic as an isolated case, the article interprets them through recurring analytical dimensions: financing, efficiency, equity, market failure and public intervention, institutional capacity, resilience, technological development, and sustainability.

Healthcare financing ♦ This dimension examines how health systems collect, pool, and spend financial resources through taxation, social insurance, private insurance, employer contributions, donor funding, and out-of-pocket payments. Financing is central to health economics because it influences access to services, financial protection, risk distribution, administrative complexity, and long-term fiscal sustainability. The comparison between tax-funded systems, social insurance models, private-insurance systems, and out-of-pocket-dominant arrangements is therefore used to evaluate how different financing structures affect equity and efficiency (WHO, 2023a).

Efficiency ♦ In this article, efficiency refers to the ability of a healthcare system to transform limited resources into the greatest possible health benefit. This includes the reduction of waste, unnecessary procedures, avoidable hospitalizations, excessive administrative costs, duplicated tests, and poorly targeted expenditure. Efficiency is analysed through concepts such as opportunity cost, cost-effectiveness analysis, cost-utility analysis, and quality-adjusted life years. These concepts are important because every health-system decision involves trade-offs between alternative uses of the same resources (Folland et al., 2021).

Equity ♦ Equity refers to the distribution of healthcare access, financial protection, and health outcomes across income groups, regions, and social categories. The article analyses equity by examining universal health coverage, out-of-pocket expenditure, workforce shortages, rural-urban differences, social determinants of health, and the unequal burden of disease. This dimension is necessary because a healthcare system cannot be considered sustainable if it improves average outcomes while leaving vulnerable populations without access to essential services.

Market failure and public intervention ♦ Healthcare markets differ from ordinary markets because they are shaped by uncertainty, information asymmetry, externalities, supplier-induced demand, monopoly power, and the moral and social importance of health. For this reason, the article analyses the role of government in correcting market failures through regulation, subsidies, public provision, price controls, public-health campaigns, insurance mandates, and emergency preparedness. This dimension is essential for explaining why healthcare cannot rely only on market mechanisms (Arrow, 1963).



Resilience ♦ Resilience refers to the capacity of health systems to respond to shocks such as pandemics, antimicrobial resistance, climate-related disasters, workforce shortages, and sudden increases in demand.

Sustainability ♦ Sustainability refers to the long-term ability of health systems to maintain access, quality, efficiency, and equity without exhausting financial, human, institutional, or environmental resources. This article therefore interprets health economics not only as a tool for cost control, but also as a framework for designing health systems that can adapt to future crises.

Table 1 summarizes the analytical framework used in the review.

Table 1. Analytical framework of the review

Analytical dimension	Main question	Examples of indicators or themes
Healthcare financing	How are healthcare resources collected, pooled, and allocated?	Taxation, social insurance, private insurance, out-of-pocket payments, donor funding
Efficiency	Are resources converted into maximum health benefit?	Cost-effectiveness, opportunity cost, waste, administrative costs, avoidable care
Equity	Who receives care and who bears the financial burden?	Universal health coverage, access gaps, catastrophic spending, social determinants
Market failure and public intervention	Why do healthcare markets fail to produce optimal outcomes?	Information asymmetry, externalities, monopoly power, supplier-induced demand
Institutional capacity	Can the system implement and govern health policies effectively?	Workforce capacity, regulation, procurement, governance, service delivery
Resilience	Can the system respond to shocks and crises?	Pandemic preparedness, emergency response, climate-health risks, supply chains
Technological development	How can innovation improve access, quality, and efficiency?	Telemedicine, AI diagnostics, digital health, disease surveillance, low-cost devices
Sustainability	Can the system maintain performance over time?	Long-term financing, prevention, equity, environmental pressure, system adaptability

This analytical framework guides the structure of the results and discussion section. The theoretical concepts of health economics are first used to explain why healthcare systems face distinctive economic problems. The global comparison then shows how these problems appear differently across income groups and financing models. The bottleneck analysis identifies the main structural barriers to efficient and equitable health systems. Finally, the policy and technological solution analysis discusses how health economics can support more sustainable healthcare reform.

2.4. Comparative and case-study approach

The article uses a comparative and case-study approach to connect general health-economic concepts with concrete institutional examples. The comparison is organized at two levels. The first level compares broad categories of health systems, including tax-funded systems, social insurance systems, private-insurance systems, and out-of-pocket-dominant models. The second level uses selected national and regional cases to illustrate how these models operate in practice and how different health-economic problems appear across income groups and institutional contexts.

The case studies were selected for their illustrative value rather than for statistical representativeness. Each case is used to clarify a broader health-economic mechanism. For example, the United States is used to illustrate how high health expenditure can coexist with market failure, administrative complexity, insurance gaps, and high household financial burden. Germany is used as an example of a social health insurance model with strong cost-control mechanisms, sickness-fund negotiations, and relatively efficient access to specialized care. Singapore is included as an example of a hybrid system that combines compulsory savings, public subsidies, catastrophic insurance, and individual choice.

Several cases are used to analyse universal health coverage and health financing in middle- and low-income settings. Brazil is discussed as an example of a large public healthcare system that expanded access while facing underfunding and waiting-time problems. Ethiopia is used to illustrate the role of community health workers and donor-supported health-system expansion. Thailand and Rwanda are included as examples of universal health coverage strategies adapted to middle- and low-income contexts, while India and Mexico are used to show the implementation difficulties that can appear when universal coverage reforms face rural infrastructure shortages, claim rejection, medicine shortages, or funding gaps.

The case-study approach also supports the analysis of structural bottlenecks and future risks. Pakistan is used in the discussion of climate-related health shocks because flooding and water insecurity, which may lead to infectious-disease outbreaks show how environmental disasters can become health-economic crises. Low-income country examples are used



to illustrate the limits of applying economic models developed in data-rich, high-income environments to contexts where informal care, donor dependency, weak data systems, and workforce shortages strongly shape health outcomes. These cases help demonstrate that health-economic analysis must be adapted to local institutional and socioeconomic conditions.

Overall, the comparative approach allows the article to avoid treating health economics as a purely abstract field. By linking theory with country examples, the review shows how financing arrangements, market failures, public intervention, equity challenges, and sustainability pressures differ across health systems. The case studies therefore function as explanatory examples that make the broader analytical framework more concrete and policy-relevant.

2.5. Methodological limitations

The methodological design of this article has several limitations. First, the article is based on a narrative review and prospective policy analysis rather than on primary data collection or econometric modelling. Therefore, its purpose is not to estimate causal effects or to test a single statistical hypothesis, but to synthesize existing evidence and interpret major health-economic patterns across different systems and contexts.

Second, the use of secondary sources creates limitations related to data comparability. International organizations, academic studies, and policy institutions may use different definitions, measurement methods, reporting years, and country classifications. For example, indicators related to health expenditure, universal health coverage, disease burden, workforce capacity, or out-of-pocket payments may not always be directly comparable across regions. This limitation is especially relevant when comparing high-income, middle-income, and low-income countries, because differences in administrative capacity and data quality can affect the reliability of reported indicators.

Third, the case studies used in the article are illustrative rather than statistically representative. Countries such as the United States, Germany, Singapore, Brazil, Ethiopia, Thailand, Rwanda, India, Mexico, and Pakistan are included because they clarify important health-economic mechanisms, not because they represent all possible healthcare systems. As a result, the conclusions drawn from these examples should be interpreted as analytical insights rather than universal generalizations.

Fourth, the global scope of the article requires a high level of synthesis. Health economics is strongly affected by local institutions, political priorities, demographic structures, epidemiological profiles, cultural expectations, and fiscal capacity. A global review can identify recurring patterns and structural bottlenecks, but it cannot fully capture all national and regional specificities. Policy recommendations must therefore be adapted to local contexts before implementation.

Finally, the article discusses several rapidly evolving areas, including pandemic preparedness, digital health, artificial intelligence, pharmaceutical access, and climate-related health risks. Because these fields change quickly, some data and policy developments may evolve after the sources used in the review. For this reason, the article should be understood as a structured synthesis of current health-economic challenges and reform directions, rather than as a final or exhaustive account of the field.

3. Results and discussion

3.1. Core health-economic mechanisms: scarcity, incentives, and market failure

Health economics begins from the problem of scarcity. Healthcare systems must allocate limited financial, human, technological, and institutional resources among competing needs such as prevention, emergency care, chronic disease management, pharmaceuticals, workforce expansion, digital infrastructure, and long-term care. Because resources used for one intervention cannot simultaneously be used for another, every healthcare decision involves opportunity cost. Opportunity-cost reasoning is also visible in institutional decision thresholds. For example, the United Kingdom's National Institute for Health and Care Excellence commonly uses a threshold of approximately £20,000–30,000 per quality-adjusted life year when assessing whether interventions should be funded (National Institute for Health and Care Excellence, 2022). This is why economic evaluation is central to healthcare policy: it helps decision-makers compare the costs and benefits of alternative interventions and identify which uses of resources generate the greatest health benefit.

However, healthcare markets differ substantially from ordinary markets. In many sectors, consumers can compare prices, delay purchases, evaluate quality, and choose between providers with relatively clear information. In healthcare, these conditions are often absent. Patients may need urgent treatment, may not understand the technical quality of care, and may depend on professional advice from physicians. This creates uncertainty and information asymmetry, meaning that providers usually know more than patients about diagnosis, treatment options, risks, and expected outcomes. As a result, healthcare cannot be analysed as a perfectly competitive market (Arrow, 1963).



Demand in healthcare is also distinctive. For life-saving or urgent services, demand is often price-inelastic because patients cannot easily reduce consumption when prices increase. Emergency care, trauma care, cancer treatment, and acute infectious-disease treatment are examples of services where need is determined more by medical urgency than by consumer preference. By contrast, demand for some elective procedures may be more price-sensitive because patients can delay, avoid, or substitute them. This difference matters for policy because high prices or co-payments may reduce necessary care for some services while having limited effect on urgent care. The difference between urgent and elective healthcare demand is summarized in *Table 2*, which illustrates how price elasticity varies across service types.

Table 2. Price elasticity variation across healthcare services (*based on Zeckhauser & Cutler (2000)*)

Service type	Price elasticity	Health-economic implication
Emergency care	-0.1, relatively inelastic	Use remains relatively stable when costs rise because treatment is urgent
Elective procedures	-0.7, more elastic	Demand may decrease significantly when patient costs increase

Another important mechanism is supplier-induced demand. Because physicians and other providers influence diagnosis and treatment decisions, their recommendations can shape patient demand. This is not necessarily negative, because patients need expert guidance. However, when financial incentives reward higher service volume, additional tests, or more expensive interventions, provider recommendations may contribute to overutilization. This can generate inefficient spending, unnecessary procedures, and higher system costs without proportional health gains (McGuire, 2012). This mechanism is supported by empirical evidence. An OECD (2023b) health-system comparison found that a 10% increase in physician density was associated with a 3–7% increase in healthcare utilization, suggesting that provider availability can influence demand as well as respond to it.

Health insurance also creates specific economic problems. Insurance protects individuals from catastrophic medical costs, but it may also create moral hazard when insured patients consume more care because they do not directly pay the full cost of each service. The U.S. insurance market before the Affordable Care Act (ACA) illustrates this problem. Before the ACA, insurers denied coverage to approximately 19% of applicants with pre-existing conditions, showing how risk selection can restrict access for the people most likely to need care. At the same time, adverse selection can occur when people with higher expected healthcare needs are more likely to purchase insurance, increasing the cost of coverage and potentially destabilizing insurance pools. These mechanisms show why health insurance markets often require regulation, risk pooling, mandates, subsidies, or public provision to remain efficient and equitable (Rothschild and Stiglitz, 1976).

Externalities further distinguish healthcare from ordinary markets. Some health interventions produce benefits beyond the individual patient. Vaccination, infectious-disease surveillance, antimicrobial stewardship, sanitation, and pandemic preparedness reduce risks for the wider population. If decisions are left only to individual willingness to pay, these interventions may be underprovided because individuals do not capture the full social benefit. The scale of positive externalities can be substantial. COVID-19 vaccination was estimated to have averted 19.8 million deaths in 2021 through direct protection and herd-immunity effects, demonstrating how individual health interventions can generate population-level benefits (Watson et al., 2022). Conversely, negative externalities such as antibiotic overuse can create broader social costs by accelerating antimicrobial resistance. This justifies public-health regulation and collective financing.

Market failure is also visible in pharmaceutical markets. Patent protection can encourage innovation by rewarding research and development, but it can also create temporary monopoly power, as patents can grant approximately 20-year monopolies on new drugs. For example, Gilead priced the hepatitis C drug sofosbuvir at approximately \$84,000 per treatment course in the United States, while production-cost estimates suggested that direct-acting antivirals could be manufactured at much lower cost. Compulsory licensing and generic competition have been used in low- and middle-income countries to reduce hepatitis C treatment prices by up to 99% (United States Senate Committee on Finance, 2015; Hill et al., 2014; Make Medicines Affordable, n.d.). When monopoly power is strong, prices may rise above production costs and restrict access to essential medicines, especially in low- and middle-income countries. This creates a tension between innovation incentives and equitable access. Health economics helps analyse this trade-off and supports policy instruments such as price regulation, reference pricing, compulsory licensing, pooled procurement, and public-private negotiation.

Government intervention can also correct market failures through regulation, mandates, communication campaigns, and taxation. Germany uses price controls to limit excessive drug prices, while the ACA expanded coverage to approximately 20 million Americans. Public-health campaigns also show measurable effects: anti-smoking policies reduced U.S. smoking



rates from 42% in 1965 to 12% in 2023, and Mexico's soda tax decreased consumption by 7.6% (Kaiser Family Foundation, 2026; Centers for Disease Control and Prevention, 2024; Colchero et al., 2016).

Overall, these mechanisms show why health systems require institutional design rather than simple market reliance. Scarcity, uncertainty, information asymmetry, inelastic demand, supplier-induced demand, moral hazard, adverse selection, externalities, and monopoly power all create conditions in which unregulated markets may fail to produce efficient or equitable outcomes. Health economics is therefore essential for identifying where markets fail, where government intervention is justified, and how healthcare systems can allocate resources in ways that support both population health and long-term sustainability.

3.2. Global patterns in healthcare systems

Health economics differs substantially across countries because healthcare systems are shaped by national income, institutional capacity, demographic structure, political priorities, and historical choices in financing and service delivery. A global perspective therefore shows that healthcare performance cannot be explained only by medical technology or total expenditure. It also depends on how resources are collected, pooled, allocated, regulated, and transformed into accessible services.

The scale of global disparity is visible in per-capita spending. Global health expenditure ranges from approximately \$41 per capita in low-income countries to around \$12,914 per capita in the United States, showing that the financial capacity of health systems differs by several orders of magnitude (WHO, 2023b).

High-income countries generally have the highest levels of healthcare expenditure, broader insurance coverage, more developed infrastructure, and stronger institutional capacity. These systems usually provide extensive access to specialized care, pharmaceuticals, diagnostic technologies, and long-term treatment for chronic diseases. However, they also face rising cost pressures caused by ageing populations, higher expectations for medical innovation, expensive pharmaceuticals, administrative complexity, and the growing burden of non-communicable diseases. In this group, the main health-economic challenge is often not the absence of resources, but the efficient and equitable management of expensive systems (WHO, 2023b). *Table 3* summarizes the main characteristics of high-income health systems, including their expenditure profile, coverage patterns, and dominant cost pressures. High-income systems also face specific cost pressures. Ageing populations increase demand for chronic disease care, while pharmaceutical costs consume approximately 15–20% of health budgets. Japan illustrates both the strengths and pressures of this group: it uses a social insurance system with 10–30% co-payments and achieves the world's highest life expectancy, approximately 84.7 years, while spending around 10.9% of GDP on healthcare (OECD, 2023b; WHO, 2023b).

Table 3. Selected characteristics of high-income health systems (based on WHO (2023b) and OECD (2023b))

Indicator	General pattern in high-income countries	Examples
Health spending	High share of GDP (10.2%) and high per-capita spending	United States (17.3%), Germany (12.6%), Switzerland
Life expectancy	Generally above 80 years (81.3 years)	Japan (84.7), Switzerland (83.4), Sweden
Universal or near-universal coverage	Common (98%), but with different financing arrangements	United Kingdom, Canada, Germany, Japan
Main pressures	Ageing, chronic disease, pharmaceutical costs, administrative complexity	Long-term care, cancer treatment, cardiovascular disease

Middle-income countries form a more heterogeneous group. Upper-middle-income countries such as Brazil, China, South Africa, and Mexico often have expanding public or mixed health systems, but they still face inequalities in access, regional disparities, and pressure from both infectious diseases and chronic conditions. Lower-middle-income countries such as India, Nigeria, the Philippines, and Vietnam generally face more serious constraints in workforce capacity, infrastructure, and public financing. Across this group, health economics is strongly concerned with how to expand universal health coverage while maintaining fiscal sustainability and improving service quality (World Bank, 2023a). The distinction between upper-middle-income and lower-middle-income countries is presented in



Table 4, which highlights differences in financing pressure, workforce availability, and universal health coverage development. Brazil's *Sistema Único de Saúde* illustrates the mixed achievements and constraints of middle-income health systems. Since 1990, Brazil has reduced infant mortality by 56% and provides free antiretroviral therapy for HIV patients. However, the system remains underfunded at approximately 3.8% of GDP. Moreover, around 25% of Brazilians use private insurance because of delays in the public system (World Bank, 2023c).



Table 4. Comparison between upper-middle-income and lower-middle-income health-system conditions (based on World Bank (2023b) and WHO (2023a))

Indicator	Upper-middle-income countries	Lower-middle-income countries
Examples	Brazil, China, South Africa, Mexico	India, Nigeria, Philippines, Vietnam
GNI/capita	\$4,466 – \$13,845	\$1,136 – \$4,465
Health-system profile	Expanding public or mixed systems	More constrained public capacity
Out-of-pocket spending	Lower than in lower-middle-income countries, but still significant: 28%	Often high and financially burdensome: 47%
Physician density	Higher, but unevenly distributed (2.9/1,000 people)	Lower and frequently concentrated in cities (1.2/1,000 people)
Universal health coverage	More developed, but unequal (68%)	Expanding, but limited by infrastructure and financing (54%)

Low-income countries face the most severe structural constraints. These include low public health expenditure, shortages of doctors and nurses, limited hospital and laboratory infrastructure, weak supply chains, donor dependency, and high vulnerability to epidemics, malnutrition, maternal and child mortality. In these systems, even basic services may remain underfunded. The health-economic problem is often how to finance essential care, strengthen primary healthcare, and reduce dependence on direct household payments. Limited fiscal space makes prioritization especially important, because the opportunity cost of every health investment is high. *Table 5* summarizes the main constraints faced by low-income health systems and their health-economic implications. Ethiopia's Health Extension Program illustrates how low-income countries can expand access through community-based capacity building. Since 2003, Ethiopia has trained approximately 40,000 community health workers and increased skilled birth attendance from 10% to 50%. However, the programme remains heavily dependent on external financing, with around 70% of funding coming from donors (World Bank, 2023c; WHO, 2023e).

Table 5. Main health-economic constraints in low-income countries (based on WHO (2023a, 2023b), and World Bank (2023b))

Constraint	Health-economic implication
Low per-capita health spending (\$41/capita)	Insufficient resources for essential services, medicines, infrastructure, and workforce
Shortage of health workers (e.g. doctor availability of 0.3 / 10,000 in Chad, 98% below WHO minimum)	Reduced access to care, especially in rural areas
High maternal and child mortality (462 / 100,000 births, 35 times higher than HICs)	Persistent burden of preventable deaths and weak primary care capacity
Donor dependency	Risk of external priority-setting and unstable financing
High out-of-pocket payments	Increased risk of catastrophic expenditure and poverty

The contrast between income groups shows that health-system sustainability has different meanings in different contexts. In high-income countries, sustainability often means controlling expenditure growth, reducing waste, improving value for money, and managing the costs of ageing and chronic disease. In middle-income countries, sustainability often means expanding coverage while preventing excessive fiscal pressure and reducing inequalities between regions and social groups. In low-income countries, sustainability requires building basic institutional capacity, increasing domestic financing, reducing donor dependency, and protecting households from catastrophic out-of-pocket payments.

These differences show why health economics must be adapted to context. A policy that is appropriate in a high-income country may not be feasible in a low-income setting, and a financing model that works in one institutional environment may fail in another. Comparative health economics is therefore essential because it identifies both general principles and context-specific constraints. The global pattern is clear: more spending can improve health-system capacity, but spending alone is not sufficient. Efficiency, equity, governance, workforce planning, and financial protection determine whether healthcare resources become sustainable improvements in population health.

3.3. Healthcare financing models and universal health coverage

Healthcare financing is one of the most important determinants of health-system performance, because it influences who pays for care, who receives access, how financial risk is distributed, and how efficiently resources are used. Although national systems vary significantly, three broad financing models are especially relevant for comparative health economics: tax-funded systems, social health insurance systems, and private-insurance or out-of-pocket-dominant systems. These models are summarized in *Table 6*, which shows their basic financing logic, strengths, and limitations.



Table 6. Main healthcare financing models (based on Folland et al. (2021) and WHO (2023a))

Financing model	Core mechanism	Main strengths	Main limitations
Tax-funded (e.g. United Kingdom)	Healthcare is financed mainly through general taxation and often provided or strongly coordinated by the state	Universal access, strong risk pooling, lower financial barriers at point of care	Waiting times, rationing, pressure on public budgets
Social health insurance (e.g. Germany)	Healthcare is financed through mandatory contributions from employers, employees, and sometimes the state	Broad coverage, pluralistic providers, relatively stable financing	Administrative complexity, contribution burden, dependence on employment structure
Private-insurance or out-of-pocket-dominance (e.g. United States)	Healthcare is financed through private insurance, employer plans, individual payments, or direct household spending	Greater consumer choice in some contexts, stronger private-sector role	Inequity, high administrative costs, financial hardship, coverage gaps

Table 7 compares three representative national financing arrangements and shows how spending, life expectancy, and infant mortality differ across the United Kingdom, Germany, and the United States.

Table 7. Comparison of three national healthcare financing systems in 2022 (based on OECD (2023b), WHO (2023b), and Commonwealth Fund (2024))

Metric	UK (National Health Service)	Germany	United States
% GDP spent on healthcare	11.1%	12.6%	17.3%
Life expectancy	81.3 years	80.6 years	77.5 years
Infant mortality	3.9 deaths / 1,000	3 deaths /1,000	5.61 deaths / 1,000

Tax-funded systems, often associated with the Beveridge Model, finance healthcare mainly through general taxation and usually provide services free or nearly free at the point of use. This model can support universal access and strong financial protection because the cost of care is pooled across the population. Countries such as the United Kingdom and Sweden illustrate how tax-funded systems can promote equity and cost control through public provision or strong public coordination. However, these systems may also face waiting times, rationing, and political pressure when public budgets are constrained. The Beveridge Model is further illustrated in Table 8 through the examples of the United Kingdom, Sweden, and Cuba. This model also shows the trade-off between equity, cost control, and waiting times. In the United Kingdom, maternal mortality is approximately 7 deaths per 100,000 live births, compared with 23.8 in the United States, while administrative costs are around 5% compared with 31% in the United States. However, rationing remains a weakness: approximately 650,000 UK patients wait more than 18 weeks for surgery, and new cancer drugs may be adopted more slowly (OECD, 2023b; Commonwealth Fund, 2024).

Table 8. Beveridge Model Healthcare systems comparisons by country in 2022 (based on OECD (2023b), WHO (2023b), and World Bank (2023b))

Country	%GDP on health	Life expectancy	Key features
UK	11.1%	81.3 years	Centralized NHS, free at point of use
Sweden	10.5%	83 years	Decentralized county management
Cuba	11.8%	77.6 years	Physician-heavy primary care

Social health insurance systems, often associated with the Bismarck Model, are financed through mandatory contributions from employers and employees, usually combined with public regulation and non-profit or semi-public insurance funds. Germany, France, and Japan illustrate this model. Social insurance can combine broad coverage with pluralistic service delivery, while sickness funds or insurers negotiate with providers and help regulate prices. However, this model can also generate administrative complexity and may require subsidies for unemployed, informal, or low-income populations in order to maintain universal coverage. Table 9 presents selected Bismarck-type systems and compares their financing mechanisms, coverage rates, and out-of-pocket (OOP) shares. Germany also illustrates the operational advantages of regulated social insurance. Sickness funds negotiate prices with providers, and reference pricing helps keep drug costs low. Germany has approximately 35 MRI scanners per million people, compared with 40 in the United States and 8 in the United Kingdom, while cardiac surgery waiting time is generally under two weeks (OECD, 2023b).



Table 9. Comparison between multiple countries with Bismarck Healthcare Model (based on OECD (2023b), WHO (2023a–b) and Folland et al. (2021))

Country	Financing mechanism	Coverage rate	OOP share
Germany	14.6% payroll tax	99%	10%
France	13% payroll + income tax	99%	7%
Japan	Employer/employee premiums	98%	12%

Private-insurance and out-of-pocket-dominant systems rely more heavily on market mechanisms, employer-based insurance, voluntary private coverage, or direct payments by patients. These systems may offer more consumer choice for some groups, but they also create major equity and financial-protection problems when coverage is incomplete or when treatment costs are high. Out-of-pocket payments are especially problematic in low- and middle-income countries, because they expose households to catastrophic health expenditure and may cause people to delay or avoid needed care. *Table 10* compares selected private-insurance or market-oriented systems, showing differences in uninsured rates, administrative costs, and drug prices. Singapore's Medisave Model shows how private responsibility can be combined with public safeguards. The system uses mandatory health savings accounts equal to approximately 8–10.5% of wages, supported by catastrophic insurance through MediShield Life. The system achieves very low infant mortality, approximately 1.8 deaths per 1,000 live births, while health spending remains around 4.5% of GDP.

Table 10 Comparison between selected private-insurance and market-oriented healthcare systems in 2022 (based on Commonwealth Fund (2024), Kaiser Family Foundation (2026), OECD (2023b), and WHO (2023b))

Metric	United States	Switzerland	Singapore
% uninsured	8.4%	0.3%	0%
Administrative costs	31%	2-3%	15-20%
Drug prices	3.5 times OECD average	1.2 times	0.8 times

Universal health coverage represents a central objective in health economics because it aims to ensure that all people can access quality essential health services without financial hardship. The United Nations Sustainable Development Goal 3.8 explicitly targets universal health coverage, including financial risk protection and access to essential healthcare services and medicines (United Nations, 2023). In practice, universal coverage does not require all countries to adopt the same financing model. Instead, it requires each system to create effective risk pooling, reduce direct financial barriers, expand service availability, and protect vulnerable groups from catastrophic expenditure. *Figure 2* summarizes regional progress toward universal health coverage and



Table 11 highlights the main barriers affecting each region.

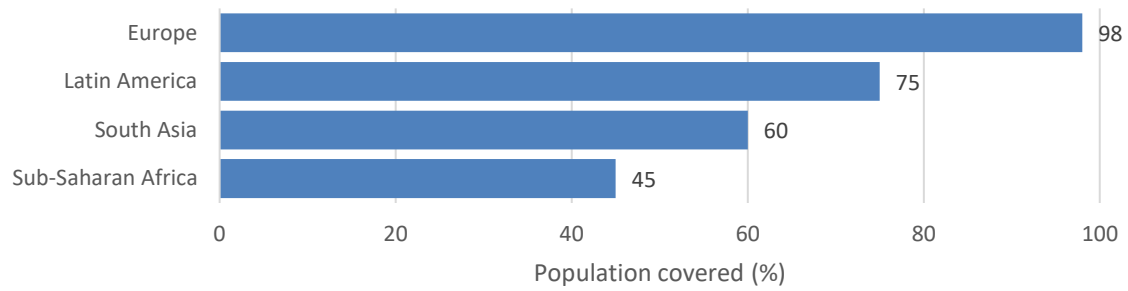


Figure 2. Universal health coverage progress across selected regions
(based on United Nations (2023), WHO (2023b), and World Bank (2023c))



Table 11. UN SDG 3.8 progress across selected regions (based on United Nations (2023), WHO (2023a), and World Bank (2023c))

Region	Key barriers
Europe	Ageing population strains system
Latin America	Informal employment (40% of workers)
South Asia	Underfunded public facilities
Sub-Saharan Africa	Doctor shortages (0.2/1,000people)

Table 12 presents selected universal health coverage cases and shows how different countries have pursued coverage expansion through different institutional pathways.

Table 12. Selected universal health coverage cases (based on WHO (2023b), World Bank (2023c), and United Nations (2023))

Case	Main mechanism	Main achievements	Main challenges
Thailand	Tax-funded universal coverage scheme with low co-payments	Expanded access to outpatient, inpatient, and emergency care; reduced catastrophic spending	Long-term fiscal pressure and demand management
Rwanda	Community-based health insurance supported by subsidies and community health workers	High enrolment, improved primary care access, stronger maternal and child health outcomes	Dependence on subsidies and administrative capacity
India	Large publicly financed hospitalization coverage for low-income households	Expanded financial protection for poor households	Rural hospital shortages, claim rejection, uneven implementation
Mexico	Transition from <i>Seguro Popular</i> to a more centralized public model	Formal objective of free care for uninsured populations	Funding gaps, medicine shortages, implementation disruption

Thailand's universal coverage strategy shows how a middle-income country can expand access through a tax-funded system adapted to national fiscal capacity. The 30-Baht Scheme was launched in 2002 after the 1997 financial crisis and was financed mainly through general taxation, approximately 67%, with a nominal co-payment of 30 Baht, around \$1, per visit. The scheme helped achieve child vaccination rates of approximately 98% and reduced catastrophic health spending from 6% to 2% of households (World Bank, 2023c; WHO, 2023a).

Rwanda illustrates a different pathway, using community-based insurance, premium subsidies, performance incentives, and community health workers to expand coverage in a lower-income setting. In the *Mutuelle de Santé* system, the poorest pay approximately \$0.5 per year compared with the standard \$5 per year. The model is supported by around 45,000 community health workers, who helped enrol approximately 90% of the population. Since 2005, malaria deaths have fallen by around 85%, and skilled birth attendance increased to approximately 90%, compared with 30% in 2000 (World Bank, 2023c; WHO, 2023b).

India and Mexico show that universal coverage reforms may face serious implementation challenges. India's *Ayushman Bharat*, launched in 2018, provides free hospitalization coverage of up to approximately \$6,000 per family per year for 500 million low-income Indians, targeting the poorest 40% of the population. However, claim rejection rates of 15–20% and the concentration of approximately 70% of facilities in cities limit its reach. Mexico replaced *Seguro Popular*, which operated from 2003 to 2019, with INSABI in 2020, aiming to provide free public care for 68 million uninsured Mexicans. However, implementation was affected by funding gaps, a 30% budget cut, and cancer drug shortages that created waits of up to six months (World Bank, 2023c; WHO, 2023a).

From a health-economic perspective, the main lesson is that financing design determines the relationship between efficiency, equity, and sustainability. Tax-funded systems may perform strongly in equity and risk pooling but depend heavily on fiscal capacity. Social insurance systems can provide stable funding and negotiated cost control but require institutional sophistication. Private-insurance and out-of-pocket systems may expand choice for some groups but often weaken equity and financial protection. Universal health coverage therefore depends less on the label of the financing model and more on whether the system can pool risk, finance essential services, control costs, and protect households from financial hardship over time.

3.4. Outstanding system cases: United States, Germany, and Singapore

The comparison between the United States, Germany, and Singapore illustrates how different institutional designs can produce very different health-economic outcomes. These cases are useful because they do not simply represent three countries, but three broader approaches to healthcare financing and governance: a highly market-oriented and



administratively complex system, a regulated social insurance model, and a hybrid system combining individual responsibility with strong public safeguards. *Table 13* summarizes the main health-economic lessons that can be drawn from these three cases.

Table 13. Comparative health-economic lessons from the United States, Germany, and Singapore (*based on Commonwealth Fund (2024), Folland et al. (2021), and WHO (2023b)*)

Country	System type	Main health-economic strength	Main health-economic weakness	General lesson
United States	Market-oriented, private-insurance-heavy system	High technological capacity and medical innovation	High costs, administrative complexity, insurance gaps, unequal access	High spending does not guarantee efficiency or equity
Germany	Social health insurance model	Broad coverage, negotiated prices, strong institutional regulation	Complex multi-payer administration and contribution burden	Regulated pluralism can combine access and cost control
Singapore	Hybrid savings, insurance, and subsidy model	Cost discipline, public safeguards, individual savings, targeted subsidies	Dependence on careful state regulation and household savings capacity	Hybrid models can balance choice and fiscal sustainability if strongly governed

The United States represents a major health-economic paradox: it spends more on healthcare than most comparable high-income countries, yet it does not consistently achieve better population-level outcomes. Its system combines employer-based insurance, private insurers, public programmes, high administrative complexity, and substantial household financial exposure. This creates a situation in which technological capacity and specialized care coexist with insurance gaps, high prices, administrative waste, and medical debt. From a health-economic perspective, the U.S. case shows that high expenditure alone is insufficient if financing is fragmented and if market failures are not corrected through effective regulation and risk pooling (Commonwealth Fund, 2024; Kaiser Family Foundation, 2026).

The magnitude of U.S. administrative waste is particularly important. Administrative waste is estimated at approximately \$812 billion per year, with billing complexity accounting for around 30% of hospital costs. The system also includes approximately 1,200 private insurers using different forms and claims procedures. Drug pricing adds another source of inefficiency: insulin costs around ten times the OECD average, and Medicare was prohibited from negotiating drug prices until 2023 (Commonwealth Fund, 2024; Kaiser Family Foundation, 2026; OECD, 2023b).

One of the central problems in the U.S. model is administrative complexity. The presence of many insurers, different reimbursement rules, complex billing procedures, and frequent claim disputes increases transaction costs for hospitals, providers, patients, and insurers. These administrative costs do not directly produce health benefits, which means that part of healthcare expenditure is absorbed by system management rather than prevention, treatment, workforce expansion, or service quality. The U.S. case therefore illustrates how inefficient institutional design can reduce value for money even in a technologically advanced health system.

Germany provides a contrasting example. Its social health insurance model relies on mandatory coverage, sickness funds, negotiated prices, and strong regulation. Rather than leaving healthcare allocation entirely to individual purchasing power, Germany uses collective financing and institutional negotiation to balance access, pluralism, and cost control. Sickness funds negotiate with providers, and reference pricing helps limit excessive pharmaceutical expenditure by setting reimbursement levels for therapeutically comparable products. Germany's system relies on approximately 110 non-profit sickness funds and collective bargaining with providers. This institutional structure helps maintain relatively short access times, with specialist waiting times generally under four weeks. Germany also has longer average hospital stays, around 7.3 days compared with 5.5 in the United States, but with lower readmission rates (OECD, 2023b; Commonwealth Fund, 2024). This structure shows how regulated competition and collective bargaining can reduce some forms of market failure while preserving patient choice and provider diversity. The performance contrast between the United States and Germany is summarized in *Table 14*.

Table 14. Healthcare services performance indicator comparison between U.S. and Germany in 2022 (*based on Commonwealth Fund (2024), OECD (2023b), and WHO (2023b)*)

Metric	U.S.	Germany	Difference
Life expectancy	77.5 years	80.6 years	-3.1 years
Preventable deaths	280/100k	249/100k	+12%



The German case is especially relevant for sustainable health economics because it demonstrates that universal or near-universal coverage can coexist with relatively efficient access to specialized care. Its strength lies not only in the amount of money spent, but in the institutional mechanisms through which resources are pooled, negotiated, and allocated. However, the system also requires strong administrative capacity and careful regulation. Social insurance models can become complex, especially when multiple funds, contribution rules, provider associations, and reimbursement mechanisms interact. Germany therefore illustrates both the advantages and the governance requirements of regulated pluralism.

Singapore represents a different model, combining compulsory medical savings, public subsidies, catastrophic insurance, and regulated patient choice. Its system is often described as hybrid because it does not rely exclusively on taxation, social insurance, or private insurance. Instead, it uses several layers of financing: individual savings for routine or predictable costs, insurance for major health risks, and state subsidies to protect affordability. This design creates incentives for cost awareness while maintaining public mechanisms that reduce the risk of catastrophic financial exposure. Singapore's hybrid model is built around *Medisave* accounts, which require mandatory income contributions of approximately 8–10.5% and cover hospitalization and chronic care. Government safeguards include price controls on around 10,000 medical services and subsidies of up to 80% for low-income patients. The system combines strong outcomes and cost discipline, including infant mortality of approximately 1.7 deaths per 1,000 live births and MRI costs of around \$300 compared with approximately \$1,200 in the United States (WHO, 2023b; OECD, 2023b).

From a health-economic perspective, Singapore shows that cost control can be pursued through a combination of individual responsibility and public regulation. However, this model also depends on specific institutional and socioeconomic conditions. Mandatory savings require sufficient household income, and cost discipline requires strong public oversight of prices, subsidies, hospital organization, and insurance design. For this reason, Singapore should not be treated as a model that can be copied mechanically in all countries. Its relevance lies in showing how hybrid financing can work when supported by high administrative capacity, careful regulation, and targeted public protection.

Together, these three cases show that no health financing model is automatically efficient, equitable, or sustainable. The U.S. demonstrates that market-driven healthcare can produce high innovation but also severe cost and access problems. Germany shows that social insurance can combine broad coverage with negotiated cost control, but requires complex governance. Singapore shows that hybrid models can maintain cost discipline, but only when individual financing is balanced by public safeguards. The broader lesson is that health-system performance depends less on ideological labels and more on the concrete design of financing, regulation, incentives, risk pooling, and institutional accountability.

3.5. Major bottlenecks in global health economics

The global comparison of health systems shows that healthcare sustainability is limited not only by financing models, but also by deeper structural bottlenecks. These bottlenecks include the growing burden of non-communicable diseases (NCDs), inefficient use of healthcare resources, weak data and modelling capacity in low-income countries, persistent inequities, emergency preparedness gaps, and climate-related health risks. *Table 15* summarizes these major bottlenecks and their health-economic implications.

Table 15 Major bottlenecks in global health economics (*Author's own synthesis.*)

Bottleneck	Main health-economic implication
Non-communicable diseases	Long-term expenditure pressure, productivity losses, and demand for chronic care
Inefficient healthcare systems	Waste, unnecessary procedures, administrative costs, and weak value for money
Weak modelling capacity in low-income countries	Poor policy targeting due to limited data and context-specific uncertainty
Health inequities and social determinants	Unequal access, preventable mortality, and reduced social welfare
Emergency preparedness gaps	High vulnerability to pandemics, supply-chain shocks, and system overload
Climate-related health risks	Rising disease burden, infrastructure stress, displacement, and productivity losses

Non-communicable diseases represent one of the most important long-term pressures on healthcare systems, accounting for approximately 74% of global deaths (WHO, 2025a). Cardiovascular diseases, diabetes, cancers, and chronic respiratory illnesses require continuous prevention, screening, medication, monitoring, and long-term treatment. This creates sustained



expenditure pressure for governments, insurers, households, and employers. The economic burden is not limited to direct medical costs; it also includes productivity losses, disability, premature mortality, and informal care. The main drivers of this burden include unhealthy diets, which are linked to around 11 million deaths per year, physical inactivity, with approximately 27% of adults insufficiently active, and tobacco use, which causes around 8 million deaths per year (IHME, 2023). These drivers show that NCDs are not only clinical problems, but also behavioural, environmental, and economic challenges. As shown in *Table 16*, the main non-communicable diseases combine large mortality burdens with major economic costs, making them central to health-economic planning.

Table 16. Selected non-communicable diseases and health-economic burden in 2022 (based on WHO (2025a) and IHME (2023))

Disease group	Yearly deaths (millions)	Main health-economic relevance
Cardiovascular diseases	19.8	High mortality, long-term treatment needs, prevention potential, and productivity losses, estimated cost of \$863 billion
Diabetes	11.0	Chronic medication, screening needs, complications, and high household cost burden, estimated cost of \$966 billion
Cancer	9.7	Expensive diagnostics, treatment innovation, long-term care, and equity concerns, estimated cost of \$1.2 trillion
Chronic respiratory diseases	4.0	Long-term management, environmental links, and pressure on primary and hospital care

South Asia illustrates the inequality of NCD management. India has approximately 77 million people with diabetes, but around 50% remain undiagnosed. For poor patients, insulin can cost around four times monthly wages, creating a major access barrier even when treatment exists (IDF Diabetes Atlas, 2023). *Table 17* shows the unequal burden of non-communicable disease management between high-income and low-income regions.

Table 17. Comparison between NCD Management in High and Low Income regions in 2022 (based on WHO (2025a) and IHME (2023))

Region	NCD Mortality Rate (/100,000 people)	Access to treatment
High-income	340–390	85%
Low-income	480–510	35%

A second bottleneck is inefficient healthcare spending. Inefficiency occurs when resources are used without producing proportional health benefits. This can include unnecessary diagnostic tests, avoidable hospital admissions, excessive administrative costs, fragmented care, low-value interventions, weak prevention, or poor coordination between providers. The problem is especially visible in systems where financial incentives reward service volume rather than health outcomes. In such cases, expenditure may increase while population health indicators improve only marginally. Health economics is therefore essential because it offers tools such as cost-effectiveness analysis, cost-utility analysis, and value-based evaluation to identify where resources are being wasted and where they could generate greater health benefits. Inefficiency has also major economic consequences. Waste accounts for approximately 20–40% of health spending, while unnecessary treatments cost around \$1 trillion per year globally. Administrative complexity also absorbs resources that could otherwise be used for care, as shown by the contrast between the United States, where bureaucracy accounts for approximately 31% of healthcare spending, and the United Kingdom, where administrative costs are closer to 5%. The United States illustrates the cost of fragmented care. Its healthcare system costs approximately \$3.6 trillion annually, yet it remains ranked last among high-income countries in efficiency (Commonwealth Fund, 2024). A major reason is that fee-for-service incentives reward service volume, which can encourage overutilization rather than prevention, coordination, or value-based care.

The measurement of disease burden is central to this efficiency challenge. Disability-adjusted life years (DALYs) and quality-adjusted life years are used to compare the impact of diseases and interventions across different conditions. Disability-adjusted life years estimate the burden created by premature mortality and years lived with disability, while quality-adjusted life years combine length and quality of life into a single measure, where 1 represents perfect health and 0 represents death (Folland et al., 2021). These indicators help policymakers compare interventions that affect different diseases and populations. However, they also require reliable data and careful ethical interpretation, because health cannot be reduced only to numerical efficiency. Figure 3 presents selected leading causes of DALYs globally: ischemic heart



disease, Low back pain, and stroke. Ischaemic heart disease primarily affected populations in Europe and South Asia, low back pain affected populations globally, and stroke imposed a particularly high burden in East Asia and Africa (IHME, 2023).

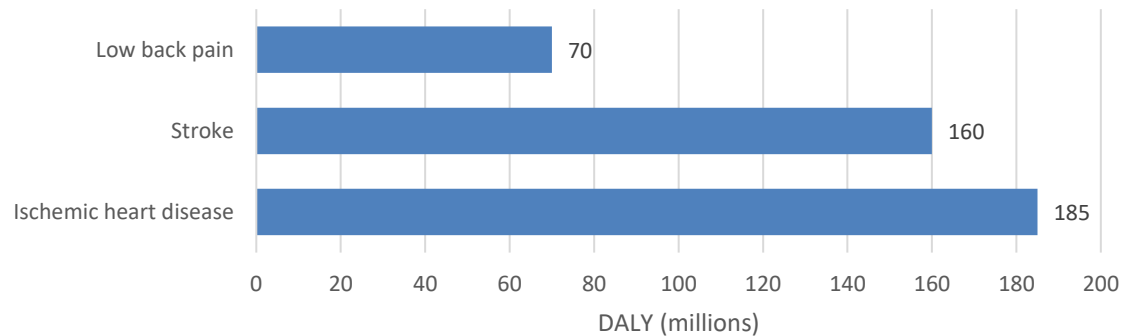


Figure 3. Leading global causes of disability-adjusted life years in 2022 (*based on IHME (2023)*)

A third bottleneck concerns the limitations of economic models in low-income countries. Many health-economic models are developed in high-income, data-rich environments where information on costs, service use, adherence, disease prevalence, and outcomes is more available. In low-income settings, data may be incomplete, informal care may play a larger role, and donor funding may distort national priorities. For example, a model developed under the assumption of stable medication access, high treatment adherence, and complete cost data may produce misleading conclusions in a context where supply chains are fragile, households pay directly for care, and health records are incomplete. This means that health-economic modelling must be localized rather than transferred mechanically from one context to another. The contrast between high-income and low-income modelling conditions can be summarized as presented in *Table 18*. HIV treatment models illustrate this limitation. Western models often assume around 95% treatment adherence, while real-world adherence rates in low-income countries may be closer to 60–70%. Donor dependency can further distort priorities: in Malawi, approximately 80% of HIV funding comes externally, which can lead to underinvestment in other chronic conditions such as hypertension (UNAIDS, 2023). This supports the need for localized modelling, such as Rwanda’s community-health-worker-driven analytics.

Table 18. Economic model use in high-income and low-income countries

Model type	High-income country application	Low-income country feasibility issue
Cost-effectiveness analysis	Approximately 85% accuracy	Often lacks local cost data
Markov simulations	Widely used	Often cannot capture informal care

Source: Author’s own synthesis.

Health inequity is another major bottleneck. Differences in income, education, geography, gender, ethnicity, and social status strongly influence access to care and health outcomes. A health system may appear efficient in aggregate terms while still failing vulnerable groups. From a health-economic perspective, this is a serious problem because preventable illness and premature mortality reduce social welfare, productivity, and human development. Equity is therefore not only a moral objective, but also an economic concern. Social determinants create large differences in life expectancy and health outcomes.

Life expectancy can vary by up to 20 years across income groups; for example, Haiti has a life expectancy of approximately 64 years, while Canada reaches around 82 years. Education also affects outcomes, as women with no schooling experience approximately 60% higher child mortality. The global distribution of surgical care is similarly unequal: the poorest 80% of people receive less than 20% of surgical care (Meara et al., 2015).

Structural inequalities also appear within high-income countries. In the United States, Black mothers are approximately three times more likely to die in childbirth, while in the United Kingdom South Asian populations face around 40% higher diabetes risk. These examples show that health inequity is not limited to low-income countries; it also appears inside wealthy systems through race, ethnicity, income, and access differences (Meara et al., 2015). Policies that improve access to



preventive care, maternal health, chronic disease management, vaccination, and primary care for disadvantaged groups can generate both health and economic benefits.

Emergency preparedness represents a further structural weakness. The COVID-19 pandemic showed that insufficient preparedness can transform health shocks into economic crises. Weak surveillance, limited laboratory capacity, shortages of protective equipment, underfunded public-health institutions, and insufficient rapid-response capacity can increase mortality, disrupt economic activity, and overload hospitals. Preparedness spending may appear costly before a crisis, but health economics shows that underinvestment in prevention and readiness can generate much higher costs during emergencies. This is especially important for infectious diseases, antimicrobial resistance, and future pandemic risks. *Figure 4* summarizes selected global preparedness gaps in disease surveillance and rapid response capacity.

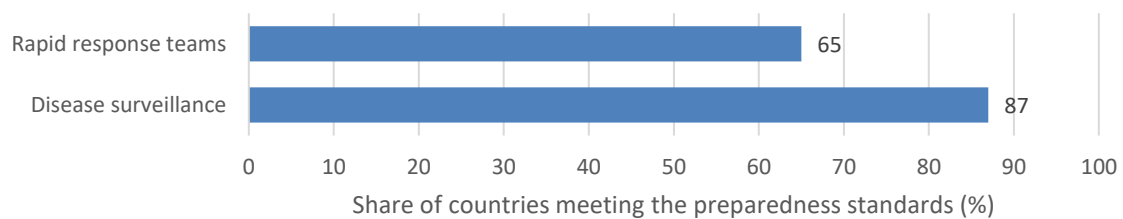


Figure 4. Share of countries meeting selected preparedness standards in 2022 (based on GPMB (2023))

Climate change is increasingly becoming a health-economic bottleneck. It is expected to cause approximately 250,000 additional deaths per year between 2030 and 2050, mainly through malnutrition, malaria, diarrhoea, and heat stress, while generating an estimated economic loss of \$2–4 billion per year (WHO, 2023c). The health impacts are already visible. The 2022 European heatwave caused more than 62,000 deaths, while asthma cases have increased by approximately 15% in high-risk zones affected by worsening air quality. Air pollution linked to wildfires and fossil-fuel combustion generates estimated health damages of around \$8.1 trillion per year. Infectious-disease risks are also shifting: dengue fever cases have increased by approximately 85% since 2000, and warmer climates are expanding malaria risk into new African highland regions. Climate-related food insecurity also creates direct health-system pressure. The Horn of Africa famine in 2022–2023 left approximately 48 million people food-insecure, increasing the risk of malnutrition and related disease. The 2022 Pakistan floods illustrate how climate shocks become health crises: they caused around 1,700 deaths, left 10 million people without clean water, and contributed to cholera outbreaks (WHO, 2023c).

Heatwaves, air pollution, floods, droughts, food insecurity, vector-borne diseases, and displacement all affect population health and healthcare demand. These risks are unequally distributed, with low-income countries, urban poor communities, outdoor workers, elderly populations, and indigenous communities often facing the greatest vulnerability. Climate-related health shocks also damage infrastructure, interrupt service delivery, increase emergency expenditure, and reduce labour productivity. Health economics must therefore include environmental risk and climate resilience in the evaluation of sustainable health systems. The economic impacts of climate-related health risks are summarized in *Table 19*. Climate-health risks are distributed unequally across populations. Mozambique, which is frequently affected by cyclones, spends around five times more on disaster recovery than on prevention. Indigenous communities also face health-system disruption, as Amazon tribes experience malaria surges linked to deforestation and land loss. Urban poor communities face additional heat exposure because slum areas can be 5–10 °C hotter than surrounding suburbs (WHO, 2023c).

Table 19. Economic impact of climate change (based on WHO (2023c), UNDP (2024), and World Bank (2023d))

Impact	Cost/Effect	Example
Disaster healthcare	\$200B/year by 2030	Pakistan floods 2022: \$16B damage
Lost productivity	2% global GDP loss by 2031	Heat reduces labor capacity by 20% in tropics
Health system strain	Hospitals overwhelmed post-disaster	Puerto Rico (Hurricane Maria): 40% clinics closed

Together, these bottlenecks show that sustainable healthcare reform cannot focus only on expanding budgets. Higher expenditure is important, but it is insufficient if health systems remain inefficient, inequitable, poorly prepared, weakly



governed, or vulnerable to climate and disease shocks. The main health-economic challenge is therefore to allocate resources in ways that reduce disease burden, protect vulnerable groups, improve preparedness, strengthen data systems, and produce long-term value for population health.

3.6. Policy and technological reform directions

The bottlenecks identified above show that health-system sustainability requires more than increased expenditure. It also requires better governance, stronger financing mechanisms, improved workforce capacity, fairer pharmaceutical access, responsible technological development, and greater resilience to future crises. Health economics contributes to these reform directions by clarifying how resources can be allocated efficiently, how incentives can be designed, and how public institutions can correct market failures while protecting equity.

A first reform direction is the strengthening of global health governance. Pandemics, antimicrobial resistance, climate-related health risks, and supply-chain disruptions cannot be managed only at national levels. They require international coordination, shared surveillance, common preparedness standards, and mechanisms for equitable access to vaccines, diagnostics, medicines, and emergency supplies. The WHO's work on the Pandemic Agreement (WHO, 2025b) and the revision of the International Health Regulations reflects this need for stronger international rules on outbreak detection, reporting, preparedness, and response (WHO, 2025b). The International Health Regulations already require countries to detect outbreaks early, report public-health emergencies to the WHO within 24 hours, and respond with science-based measures. As of 2023, 194 countries were involved in negotiations on stronger legally binding commitments, although national sovereignty concerns and funding gaps remain major obstacles. From a health-economic perspective, preparedness financing should be interpreted as an investment rather than a cost, because underinvestment before crises can generate much higher health and economic losses during emergencies.

The broader international framework is Sustainable Development Goal 3 (SDG 3), adopted in 2015 as part of the 2030 Agenda for Sustainable Development (United Nations, 2015). SDG 3 includes 13 targets and 28 indicators, including reducing global maternal mortality to below 70 deaths per 100,000 live births, ending preventable newborn deaths by reducing neonatal mortality to 12 or fewer deaths per 1,000 live births, reducing under-five mortality to 25 or fewer deaths per 1,000, and reducing premature deaths from non-communicable diseases by one third through prevention and treatment (United Nations, 2023).

Progress toward SDG 3 remains mixed. Child mortality has fallen by approximately 50% since 2000, HIV treatment access has risen to around 75% of infected individuals, and vaccination coverage has improved despite disruption during COVID-19. However, the SDG agenda faces major obstacles, including an estimated \$5.9 trillion funding shortfall by 2030, climate-related health risks, and fragile health systems in conflict zones such as Yemen and South Sudan (United Nations, 2023; UNAIDS, 2023).

Table 20 presents examples health initiatives led by intergovernmental organizations (IGOs), their achievements, and remaining challenges.

Table 20 Effectiveness of IGO-Led Health Initiatives (based on Gavi (2024), Global Polio Eradication Initiative (n.d.), WHO (2023d), and The Global Fund (2023))

Initiative	Key achievement	Remaining challenges
Gavi, the vaccine Alliance	Vaccinated 1 billion children	Equitable distribution issues
Global Polio Eradication	99% reduction in polio cases	Last-mile delivery in conflict zones
WHO's Tobacco Control	62 countries adopted strict policies	Industry lobbying undermines progress

The Global Fund provides a major example of large-scale intergovernmental health financing. Since 2002, it has disbursed approximately \$55 billion, supported 24.5 million people on antiretroviral therapy, and contributed to a 68% reduction in AIDS-related deaths since the peak (The Global Fund, 2023).

A key mechanism proposed under the Pandemic Agreement (WHO, 2025b) is Pathogen Access and Benefit-Sharing. Under this mechanism, countries would share virus samples or genomic data within 24–72 hours of detection, while manufacturers would allocate approximately 20% of vaccines, tests, or related products to low- and middle-income countries at non-profit prices. This mechanism aims to correct the unequal access patterns seen during COVID-19, although pharmaceutical companies such as Moderna and Pfizer have opposed mandatory technology-transfer requirements (WHO, 2025b). The agreement also includes equity mechanisms such as WHO-coordinated stockpiles of personal protective



equipment, antivirals, and vaccines for low- and middle-income countries, as well as possible temporary patent waivers during emergencies. Accountability mechanisms may include independent monitoring of preparedness metrics such as laboratory capacity and surge staffing, with possible penalties for non-compliance. However, major challenges remain, including sovereignty concerns from powerful states and the unresolved question of who should finance the proposed \$10 billion per year preparedness fund (WHO, 2025b).

A second reform direction concerns equitable health financing. Low- and middle-income countries often face limited fiscal space, high out-of-pocket payments, donor dependency, and competing public priorities. Expanding fiscal space for health can involve domestic resource mobilization, better tax collection, targeted sin taxes, debt relief mechanisms, and international financing instruments. Specific fiscal mechanisms show how domestic revenue can support health policy. The Philippines raised approximately \$1.2 billion per year from sugar taxation, while Mozambique redirected approximately \$200 million from debt repayment to healthcare through debt-for-health swaps (WEMOS, 2024). Performance-based financing initiatives, such as the World Bank's Global Financing Facility (GFF), show how external and domestic resources can be linked to maternal, newborn, child, and adolescent health priorities while strengthening data systems and primary healthcare capacity. The GFF was launched in 2015 by the World Bank in partnership with the United Nations and other multilateral organizations. Its model is based on country-led investment cases that prioritize high-impact interventions such as antenatal care, immunization, supply chains, and workforce development. It combines domestic resources, usually 60–70% of funding, with international aid, usually 30–40%, from sources such as the World Bank, bilateral donors including Canada and Norway, and private-sector actors such as the Gates Foundation. Funds are released after countries achieve agreed targets; for example, Ethiopia received additional GFF funds after increasing contraceptive access by 25%. Across supported regions, the GFF has been associated with a 27% reduction in maternal mortality (GFF, n.d.).

A third reform direction is investment in the health workforce. Shortages of doctors, nurses, midwives, community health workers, and public-health professionals limit access to care and reduce system resilience. Workforce expansion is especially important in low-income and rural settings, where physical infrastructure may exist but remain ineffective because there are too few trained professionals to deliver services. Task-shifting can improve access by training community health workers to provide preventive care, health education, basic treatment, maternal health support, and chronic disease follow-up. This approach is particularly relevant when specialist capacity is limited and when early intervention can prevent expensive hospital care. Rwanda illustrates the potential of task-shifting, as approximately 45,000 community health workers contributed to a 60% reduction in malaria deaths. Brain-drain mitigation also requires active policy design, such as ethical recruitment under the WHO Global Code of Practice and bonded scholarships for medical students, as used in Zimbabwe (Sewankambo, 2016).

A fourth priority is improving pharmaceutical access. Medicines are central to health outcomes, but pricing, patents, procurement inefficiencies, and supply-chain weaknesses can restrict access, especially in low- and middle-income countries. Health economics helps identify the trade-off between rewarding innovation and ensuring affordability. Policy instruments such as pooled procurement, price negotiation, generic competition, reference pricing, and compulsory licensing can reduce costs while maintaining access to essential medicines. For example, Malaysia used compulsory licensing for hepatitis C drugs, reducing treatment costs by approximately 99%. Pooled procurement can also reduce access barriers: the African Union's Africa Medical Supplies Platform saved approximately \$1 billion on drug purchases (Make Medicines Affordable, n.d.).

Technological development represents another major reform pathway. Telemedicine, mobile health, digital surveillance, artificial intelligence, low-cost diagnostics, and climate-resilient infrastructure can improve access, quality, and efficiency, particularly in underserved areas. Digital consultations can reduce geographic barriers; AI-supported diagnostics can help address specialist shortages; mobile health platforms can support maternal care, adherence, and prevention; and digital disease surveillance can improve early outbreak detection. However, technology should not be treated as a universal solution. Its benefits depend on infrastructure, regulation, data quality, affordability, digital literacy, and integration with existing health systems.

Table 21 summarizes the main policy and technological reform directions discussed in this section and links them to their expected health-economic effects.



Table 21. Policy and technological reform directions in health economics (based on *Global Financing Facility (n.d.)*, *Make Medicines Affordable (n.d.)*, *Hwang et al. (2024)*, *UNDP (2024)*, and *WHO (2025a)*.)

Reform direction	Main mechanism	Expected health-economic effect
Global health governance	International rules, surveillance, preparedness agreements, emergency coordination	Lower crisis costs, faster response, stronger collective resilience
Equitable health financing	Domestic resource mobilization, targeted taxes, debt relief, pooled funds, performance-based financing	Reduced out-of-pocket burden, stronger financial protection, expanded service access
Health workforce investment	Training, task-shifting, retention strategies, community health workers	Improved primary care access, lower preventable mortality, reduced hospital pressure
Pharmaceutical access reform	Price negotiation, generic competition, pooled procurement, compulsory licensing	Lower medicine costs, improved treatment access, reduced monopoly pressure
Digital health and AI	Telemedicine, AI diagnostics, mHealth, digital surveillance	Expanded access, faster diagnosis, improved efficiency, better monitoring
Sustainable health technologies	Low-cost devices, solar-powered clinics, resilient infrastructure	Improved service delivery in low-resource settings, lower environmental vulnerability

Artificial intelligence and digital health deserve particular attention because they can reshape healthcare delivery and resource allocation. AI-supported screening, radiology tools, and diagnostic algorithms may reduce the time and cost required to identify certain diseases, especially where specialists are scarce. Telemedicine can connect rural patients with urban providers, while mobile health platforms can support health education, appointment reminders, maternal health follow-up, and chronic disease management. Evidence on AI-supported diagnostics suggests potential efficiency gains, but these tools must be validated and monitored, and made transparent to avoid bias, unsafe recommendations, or unequal access (Hwang et al., 2024; Fu et al., 2025). *Table 22* summarizes selected health technologies and their reported applications and cost-effectiveness.

Digital health already shows large-scale implementation. India's *eSanjeevani* platform handled approximately 100 million consultations between 2020 and 2023, demonstrating the ability of telemedicine to expand access at scale (Sood et al., 2025). AI-powered tuberculosis screening in Kenya improved detection rates by approximately 40%, showing how diagnostic algorithms can support care in specialist-constrained settings (Hwang et al., 2024).

Table 22. Effectiveness of selected international health initiatives (based on *Hwang et al. (2024)*, *Fu et al. (2025)*, *Qure.ai (n.d.)*, *South African National Department of Health (n.d.)*, and *UNDP (2024)*)

Technology	Application	Cost-effectiveness
AI Radiology (Qure.ai)	90% accuracy in detecting lung diseases	\$0.5/scan in India
Blockchain for Supply Chains	Reduced counterfeit drugs by 70% in Ghana	\$2M implementation cost
mHealth (MomConnect)	4 million South African mothers receiving SMS care tips	\$0.1/user/month

Digital surveillance and personalized medicine also show health-economic potential. The WHO's Epidemic Intelligence from Open Sources system detected approximately 85% of outbreaks early, while genomic sequencing for precision oncology reduced cancer treatment costs by around 25% (Fu et al., 2025).

Sustainable health technologies are also increasingly important. Low-cost diagnostic devices, portable imaging tools, solar-powered clinics, and climate-resilient infrastructure can improve service delivery in regions where electricity, transport, and hospital infrastructure are limited. For example, the Butterfly iQ foldable ultrasound costs approximately \$2,000 compared with around \$100,000 for traditional machines, while paper-based malaria diagnostic tests can cost approximately \$0.10 per unit (UNDP, 2024).

Climate-resilient infrastructure can also improve health-system continuity. Nigeria's Solar for Health Initiative electrified approximately 500 clinics, while the UK NHS Net-Zero Plan reduced emissions by approximately 30% since 2020 (UNDP, 2024; NHS England, 2022). These examples show that sustainable health technologies can support both service delivery and environmental objectives. These technologies are relevant not only for environmental sustainability, but also for equity and resilience. A clinic that can maintain electricity during climate-related disruptions, for example, is better able to preserve vaccine storage, emergency care, maternal services, and disease surveillance. This connects health economics with



sustainable development because infrastructure choices influence both current access and future system vulnerability (UNDP, 2024).

Technology integration also requires regulation and public-private governance. The WHO's 2021 AI ethics guidelines emphasize transparency, accountability, and bias mitigation, while the EU AI Act of 2024 imposes strict validation requirements for high-risk medical AI (WHO, 2021; European Parliament and Council of the European Union, 2024). Public-private partnerships can also support implementation, such as Google Health and the Kenyan Ministry of Health's AI diabetic retinopathy screening project for 5 million patients, and Pfizer and BioNTech's mRNA hubs in Africa, which aim to reduce dependence on vaccine imports (Asonitou et al., 2024).

Overall, the reform agenda suggested by health economics is multidimensional. Stronger governance improves preparedness; equitable financing protects households; workforce investment expands real service capacity; pharmaceutical reform improves affordability; and responsible technology can increase access and efficiency. The central challenge is to combine these reforms rather than treat them separately. A sustainable health system requires financing, institutions, human resources, medicines, digital tools, and infrastructure to work together toward the same goal: producing better health outcomes with limited resources while protecting equity and resilience.

3.7. Synthesis: health economics and sustainable system transformation

The findings discussed in the previous sections show that health economics is not simply a technical field concerned with healthcare expenditure. It is a framework for understanding how health systems can transform limited resources into population health, financial protection, institutional resilience, and long-term sustainability. The central issue is not only whether countries spend more or less on healthcare, but whether spending is organized through financing mechanisms, incentives, governance structures, and delivery models that produce equitable and efficient outcomes.

A first synthesis point is that sustainability requires efficiency. Health systems cannot remain sustainable if large shares of expenditure are absorbed by administrative complexity, avoidable hospitalizations, low-value interventions, unnecessary procedures, or poorly coordinated care. Economic evaluation tools such as cost-effectiveness analysis, cost-utility analysis, and opportunity-cost reasoning help identify which interventions generate the greatest health benefit for available resources. This does not mean that policy should focus only on cost reduction. Rather, it means that health systems should redirect resources away from waste and toward interventions with stronger population-health value, including prevention, primary care, workforce development, and early diagnosis (Folland et al., 2021).

A second synthesis point is that sustainability requires equity. A system that improves average outcomes while excluding vulnerable populations cannot be considered socially or economically sustainable. Inequitable access to healthcare increases preventable illness, disability, premature mortality, and household financial hardship. Universal health coverage therefore becomes a key sustainability objective because it connects access to services with protection from catastrophic expenditure. Health economics contributes to this goal by analysing how financing models, insurance design, subsidies, public provision, and risk pooling affect the distribution of both benefits and costs (WHO, 2023a).

A third synthesis point is that sustainability requires correction of market failures. Healthcare markets are affected by uncertainty, information asymmetry, externalities, supplier-induced demand, moral hazard, adverse selection, and monopoly power. These mechanisms explain why unregulated healthcare markets may produce high costs, unequal access, underinvestment in prevention, and inefficient allocation of resources. Public intervention is therefore not external to health economics; it is one of its central concerns. Regulation, public financing, collective bargaining, price negotiation, vaccination programmes, pandemic preparedness, and pharmaceutical access policies are all examples of how institutions can correct market failures and protect social welfare (Arrow, 1963).

A fourth synthesis point is that sustainability requires resilience. The COVID-19 pandemic, antimicrobial resistance, climate-related disasters, workforce shortages, and supply-chain disruptions show that health systems must be prepared for shocks. A system may appear efficient in normal conditions but fail during emergencies if it lacks surveillance capacity, emergency reserves, flexible financing, trained personnel, and coordinated governance. Health economics therefore needs to treat preparedness as a long-term investment. Spending on surveillance, primary care, workforce capacity, and climate-resilient infrastructure may reduce future losses by preventing crises from becoming larger health and economic disasters.

A fifth synthesis point is that technological innovation must be integrated responsibly. Digital health, telemedicine, artificial intelligence, mobile health platforms, low-cost diagnostics, and climate-resilient technologies can improve access and efficiency, especially in underserved regions. However, technology alone does not solve structural problems. Without regulation, validation, data protection, affordability, infrastructure, and workforce integration, digital tools may reproduce



inequalities or create new risks. Health economics can support responsible innovation by asking whether technologies are cost-effective, equitable, scalable, safe, and aligned with public-health priorities.

Table 23 summarizes the main ways in which health economics contributes to sustainable health-system transformation.

Table 23. Contributions of health economics to sustainable health-system transformation (*Author's own synthesis*)

Sustainability objective	Health-economic contribution	Expected system effect
Efficiency	Identifies waste, opportunity costs, and high-value interventions	Better use of limited resources
Equity	Assesses access, financial protection, and distributional effects	Reduced inequality and catastrophic expenditure
Market correction	Analyses information asymmetry, externalities, monopoly power, and insurance failures	Stronger regulation and fairer allocation
Resilience	Evaluates preparedness, workforce capacity, and crisis-response investment	Greater ability to absorb shocks
Responsible innovation	Assesses cost-effectiveness, safety, scalability, and access to technology	Better integration of digital and sustainable health technologies
Long-term sustainability	Connects financing, governance, prevention, and institutional capacity	Health systems able to maintain performance over time

Overall, sustainable health-system transformation requires the integration of these dimensions. Efficiency without equity can reduce costs while excluding vulnerable groups. Equity without efficiency can expand access but create unsustainable fiscal pressure. Technology without governance can increase complexity or inequality. Preparedness without stable financing can remain only a formal objective. Health economics is valuable because it connects these dimensions into a single analytical framework. It helps policymakers evaluate not only how much should be spent, but how resources should be organized, for whom, through which institutions, and with what long-term consequences.

The broader implication is that health economics should be placed at the centre of health-system reform. In the coming decades, countries will face increasing pressure from ageing populations, chronic diseases, antimicrobial resistance, climate change, technological disruption, and fiscal constraints. Responding to these challenges requires more than isolated reforms. It requires integrated policy design that aligns financing, incentives, workforce capacity, pharmaceutical access, digital innovation, and public-health preparedness. Health economics provides the conceptual and practical tools needed to guide this transformation toward systems that are more efficient, equitable, resilient, and sustainable.

4. Conclusion

This article reviewed health economics as a framework for understanding and improving the efficiency, equity, resilience, and sustainability of healthcare systems. The analysis showed that health systems face a growing convergence of pressures, including non-communicable diseases, rising expenditure, unequal access to care, workforce shortages, inefficient resource allocation, pandemic risk, climate-related health threats, and technological disruption. These challenges affect countries differently, but they all require economic reasoning because healthcare resources are limited and policy choices involve trade-offs.

4.1. Summary of main findings

The review first showed that healthcare markets differ from ordinary markets because they are shaped by uncertainty, information asymmetry, externalities, supplier-induced demand, moral hazard, adverse selection, and monopoly power. These mechanisms explain why unregulated healthcare markets may generate high costs, unequal access, underinvestment in prevention, and inefficient allocation of resources. Health economics is therefore essential for identifying where market failures occur and where public intervention, regulation, risk pooling, or collective financing may be justified.

The comparative analysis also showed that health-system performance depends not only on the amount of money spent, but on how resources are financed, pooled, governed, and distributed. High-income countries generally face problems of cost control, ageing, administrative complexity, and chronic disease management. Middle-income countries often face the challenge of expanding universal health coverage while maintaining fiscal sustainability. Low-income countries face more fundamental constraints related to workforce shortages, donor dependency, weak infrastructure, out-of-pocket payments, and limited data capacity.

The article further identified major bottlenecks that limit sustainable healthcare reform: non-communicable diseases, inefficient spending, weak modelling capacity in low-income settings, social inequities, emergency preparedness gaps, and



climate-related health risks. Finally, the review discussed reform directions including stronger global health governance, equitable financing, health workforce investment, pharmaceutical access reform, digital health, artificial intelligence, and sustainable health technologies. Overall, the main finding is that health economics should be understood not only as a tool for controlling costs, but as a policy framework for designing healthcare systems that are more efficient, fair, adaptive, and sustainable.

4.2. Significance and original contribution

The significance of this article lies in its integration of health economics with the broader objective of sustainable health-system transformation. Health economics is often associated with cost control, expenditure analysis, or technical evaluation of interventions. However, the review shows that its relevance is wider: it provides a framework for connecting financing, efficiency, equity, market failure, public intervention, institutional resilience, and technological change. This broader perspective is important because contemporary health systems are not challenged by a single problem, but by the interaction of multiple pressures that affect both population health and economic stability.

The article's original contribution is its synthesis of theoretical concepts, global health-system comparisons, structural bottlenecks, and reform directions within one integrated framework. By linking concepts such as opportunity cost, information asymmetry, externalities, insurance failure, and cost-effectiveness with practical issues such as universal health coverage, workforce shortages, pharmaceutical access, digital health, and climate-related risks, the article shows how health economics can support policy design across different national contexts.

Another contribution is the emphasis on sustainability as a multidimensional objective. A sustainable health system is not only one that spends less, but one that uses resources efficiently, protects vulnerable populations, corrects market failures, prepares for shocks, and adapts to technological and environmental change. This approach helps move the discussion beyond the simple contrast between public and private healthcare models. Instead, it highlights the importance of institutional design, governance capacity, risk pooling, regulation, and long-term investment.

The article therefore contributes to the field by presenting health economics as a practical policy framework for improving healthcare systems under conditions of scarcity and uncertainty. Its main value is to show that efficiency, equity, and resilience should not be treated as separate goals, but as interconnected dimensions of sustainable healthcare reform.

4.3. Limitations of the review

This article has several limitations. First, it is based on a narrative global review and prospective policy analysis rather than on primary data collection, statistical modelling, or econometric testing. As a result, the article does not estimate causal relationships between specific policies and health outcomes. Its purpose is instead to synthesize existing evidence, compare major health-system patterns, and identify relevant policy directions.

Second, the review relies on secondary sources, including international reports, policy documents, and academic literature. Although these sources are useful for global comparison, they may differ in methodology, reporting year, definitions, and measurement approach. Indicators such as health expenditure, universal health coverage, disease burden, workforce capacity, and out-of-pocket payments may therefore not always be perfectly comparable across countries or regions.

Third, the country examples used in the article are illustrative rather than exhaustive. Cases such as the United States, Germany, Singapore, Brazil, Ethiopia, Thailand, Rwanda, India, Mexico, and Pakistan were selected because they help explain broader health-economic mechanisms. They should not be interpreted as a complete classification of all healthcare systems or as statistically representative of their income groups.

Fourth, the global scope of the article limits the level of detail that can be provided for each national context. Healthcare systems are shaped by local institutions, political choices, demographic structures, cultural expectations, epidemiological profiles, and fiscal capacity. For this reason, the policy directions discussed in the article should be adapted to each country before implementation.

Finally, several topics discussed in the article, including artificial intelligence, digital health, pandemic preparedness, pharmaceutical access, and climate-related health risks, are rapidly evolving. Future policy changes, technological developments, or new health crises may alter the relevance or urgency of some findings. Therefore, the article should be understood as a structured synthesis of current health-economic challenges and reform directions, not as a final or exhaustive account of the field.

4.4. Future research and final remarks



Future research should develop more detailed country-specific and region-specific analyses of the health-economic challenges identified in this article. While global reviews are useful for identifying broad patterns, national health systems require locally adapted evidence. Further studies could examine how different financing models affect access, efficiency, and financial protection in specific institutional contexts. Quantitative research could also estimate the impact of universal health coverage reforms, workforce investments, pharmaceutical pricing policies, or digital health interventions on health outcomes and public expenditure.

Another important research direction concerns health economics in low- and middle-income countries. More localized data are needed on costs, service utilization, treatment adherence, informal care, workforce distribution, and household financial burden. Strengthening local data systems would improve the reliability of economic evaluations and reduce the risk of applying models developed in high-income countries to contexts where assumptions may not hold. Future studies should therefore focus on developing context-sensitive methods for evaluating healthcare interventions in data-limited settings.

Digital health and artificial intelligence also require further health-economic evaluation. Future research should assess not only whether these technologies are technically accurate, but also whether they are cost-effective, equitable, scalable, safe, and integrated into real healthcare workflows. Particular attention should be given to bias, data protection, regulatory standards, infrastructure requirements, and the risk that digital technologies could widen inequalities if they are accessible only to better-resourced populations.

Climate-related health risks represent another growing area for future research. Health economics should increasingly examine the costs of heatwaves, floods, air pollution, food insecurity, infectious-disease spread, and climate-related displacement. More research is also needed on the economic value of climate-resilient health infrastructure, preventive public-health measures, and sustainable medical technologies.

In conclusion, health economics offers an essential framework for healthcare reform in a period of scarcity, uncertainty, and global pressure. Its value lies in connecting efficiency with equity, financing with access, innovation with regulation, and present expenditure with future resilience. Sustainable healthcare systems will require not only more resources, but better allocation, stronger institutions, fairer financing, and long-term investment in prevention, preparedness, workforce capacity, and responsible technological development. Health economics can guide this transformation by helping policymakers design systems that produce better health outcomes while remaining financially, socially, and institutionally sustainable.

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Sustainability challenges of Hungarian lakeside destinations – Lake Balaton and Lake Velence

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Abstract

Lakeside settlements are among the tourist destinations most exposed to climate change and anthropogenic pressure. In landlocked Hungary, Lake Balaton and Lake Velence are key destinations, and in the summer of 2026 both saw a marked decline in visitor traffic. This paper examines how climate change, anthropogenic pressure and economic factors jointly affect the sustainability of the two destinations, and outlines regulatory directions for adapting their tourism. The study draws on recent scientific literature, statistics, the results of an earlier visitor survey and expert statements reported in the press. The findings show that rising water temperatures, more frequent heatwaves and droughts, falling water levels and deteriorating ecological status directly threaten the natural basis of bathing-based tourism, with Lake Velence being the most vulnerable. These effects are compounded by the overdevelopment of the shoreline and the degrading quality of reed beds. Demand is further weakened by economic factors such as the strong forint (HUF) and the growing attractiveness of foreign destinations. A fall of around 20% in hospitality turnover on the southern shore of Lake Balaton and in attendance at the main beach in Siófok, together with a 5.2% decrease in foreign guests at Lake Balaton, illustrates the problem. The paper concludes that preserving the tourist appeal of Hungarian lakes requires sustainable lake management, with special emphasis on the protection of shoreline habitats and restrictions on construction. Furthermore, the tourism offer should be diversified and regulations should facilitate the sustainable development of lakeside tourist destinations.

Keywords

climate change, lake tourism, sustainable tourism, Lake Balaton, Lake Velence

1. Introduction

Tourism is one of the economic sectors that respond most sensitively to changes in the natural environment. Tourist destinations built on natural and recreational resources – landscapes, bodies of water, forests and mountain areas – are particularly vulnerable to climatic change and anthropogenic pressure. The relationship is two-way: while climate change threatens destinations, tourism itself contributes to environmental degradation through emissions, land use and resource consumption (Mann et al., 2025).

This has been felt in Hungary as well: in the summer of 2026, visitor numbers at Lake Balaton and Lake Velence, both traditionally major attractions, fell considerably. The strengthening of the Hungarian currency also contributed to this, as a result of which Hungarian tourists visited the Croatian coast in greater numbers instead. Given that increasingly frequent drought summers and heatwaves that count as extreme under Carpathian Basin conditions must be reckoned with in the near future, solutions must be found to the problems of tourist destinations that rely on bodies of water.

In this article I address this complex set of problems and outline proposals for transforming tourism in the regions concerned. In line with the concept of cognitive sustainability, which emphasises the role of knowledge, awareness and

cognitive capabilities in shaping sustainable processes (Zöldy et al., 2022), the article also considers how stakeholders perceive and respond to these changes.

2. Data and methods

The study is a qualitative, exploratory case study of two Hungarian lakeside destinations, Lake Balaton and Lake Velence. The two lakes were selected because they are the country's most important bathing lakes and, as shallow lakes, both are highly sensitive to climate change, while differing in size, tourist appeal and the severity of the problems they currently face. This makes it possible to compare a destination under acute pressure (Lake Velence, 11 km long) with one where similar processes are at an earlier stage (Lake Balaton, 77 km long) (Figure 1). The analysis focuses on the 2026 summer season, placed in the context of longer-term trends.

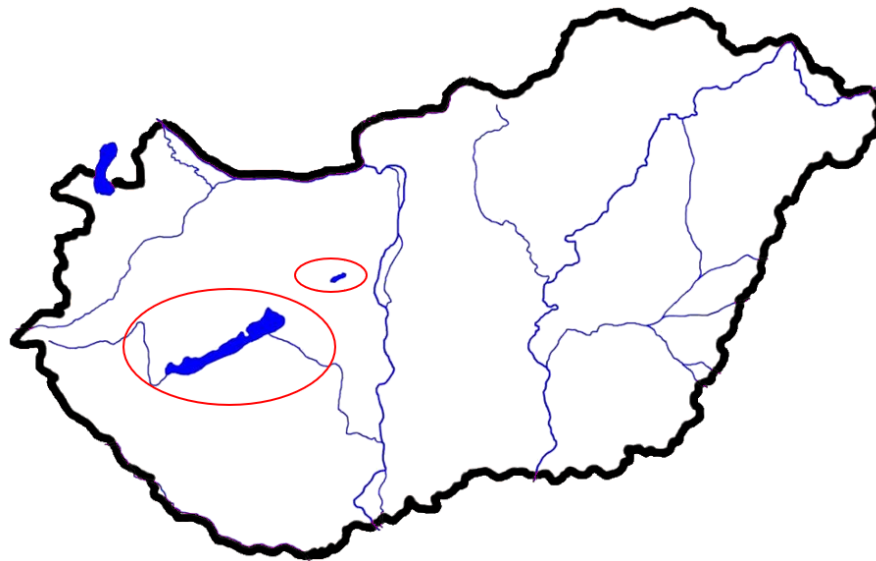


Figure 1. Lake Balaton (left) and Lake Velence (right) (Edited by the author)

The research is based on secondary data from four types of source. (1) Peer-reviewed scientific literature, complemented by a popular-science summary of long-term water temperature measurements by researchers of the Balaton Limnological Research Institute (Tóth and Li, 2025); (2) The results of an earlier questionnaire survey of visitor preferences at Lake Velence (Wirth, 2017), used to assess how dependent the destination is on bathing. (3) Official statistics by the Hungarian Central Statistical Office (KSH, 2026). (4) Articles published in the Hungarian national economic and tourism press between July and September 2026, which report data and statements from key stakeholders. These sources are complemented by the author's own field observations, made on the shoreline of Lake Velence at Velence in April 2026 and at Lake Balaton in September 2026.

The material was analysed through qualitative content analysis. The information was grouped into three dimensions: (a) climatic and hydrological changes, (b) anthropogenic and ecological pressures, and (c) economic factors affecting tourism demand. Wherever possible, figures reported in the press were cross-checked against official statistics, and discrepancies between sources are discussed explicitly. On this basis, the study identifies the main risks to lakeside tourism and formulates regulatory directions for its adaptation.

The study has several limitations. Press sources are not peer reviewed and partly reflect the interests of the stakeholders quoted; the official statistics cover a single month; the field observations were not systematic; and no primary data were collected. The relative contribution of climatic and economic factors to the decline in tourism therefore cannot be quantified here, which remains a task for further research.

3. Results and discussion

In recent decades, clearly perceptible trends have been observed in many parts of Europe, including Hungary, in changing temperature conditions, in the uneven distribution of precipitation, and in the increasing frequency of extreme weather



events. At the same time, tourist traffic is growing, and the recreational pressure on protected natural areas is intensifying. As a consequence, tourism infrastructure is expanding – not infrequently in ecologically vulnerable areas (Robak, 2026).

According to regional climate models, significant changes in climatic conditions are expected in Hungary: an increase in the number of heatwave days, on which the daily mean temperature exceeds 25 °C, is anticipated, as is a higher frequency of heavy rainfall (Sági and Buzási, 2024).

In landlocked countries, including Hungary, lakes are major tourist attractions. It is therefore a very serious problem that they are particularly sensitive to the extreme drought caused by climate change. Water levels are declining in about half of the world's lakes. In addition, lake ecosystems are severely affected by oxygen depletion resulting from heatwaves, which can lead to fish kills and algal blooms. These processes, in turn, also affect the use of lakes for tourism (Woolway et al., 2025).

Climate change manifests itself primarily through the transformation of hydrological conditions, the rise in surface water temperatures, the increasing frequency of extreme precipitation events, and the shortening of recreational seasons. Anthropogenic pressure, by contrast, is reflected in the recreational overloading of natural sites, the pollution of water resources, and the uncontrolled development of tourism infrastructure (Robak, 2026).

The decline is also reflected in the figures: for example, the turnover of hospitality businesses on the southern shore of Lake Balaton fell by around 20 per cent this year compared with 2025 (Turizmus.com, 2026). This is somewhat contradicted by data published by the Hungarian Central Statistical Office (KSH) in September 2026, according to which the number of domestic guests arriving at tourist accommodation around Lake Balaton rose by 1.8% (KSH, 2026). It is also true, however, that the number of foreign guests arriving at tourist accommodation was 3.0% lower in Budapest and 5.2% lower at Lake Balaton (KSH, 2026). Among the most important source countries, considerably fewer visitors came to Lake Balaton in 2026 than a year earlier from Slovakia, Germany and the Czech Republic (Pénzcentrum, 2026). At national level, the KSH data – also reported by Infostart (2026b) – show that the number of guests decreased by 0.4 per cent, while the number of guest nights increased by 0.3 per cent compared with the previous year (KSH, 2026).

However, the tourist appeal of Lake Balaton and Lake Velence has declined not only because of the direct problems arising from climate change; the growing purchasing power of the Hungarian currency, the forint (HUF), has also played a part. In the summer of 2026, for example, owing to the strong Hungarian currency, far more Hungarians visited the Croatian coast than in any previous year (Járdi, 2026).

According to Péter Makkos, head of the South Balaton group of the Association of Retail and Hospitality Entrepreneurs (KISOSZ), it must be accepted that “water and sunshine cannot be sold at the price of gold”, referring to the cost of a holiday for a family, including parking fees, beach admission and charges for toilets. Because of falling turnover, high costs and labour shortages, many lakeside hospitality businesses have fallen into crisis; some have given up, while others now open only at weekends (Turizmus.com, 2026). Beyond the economic difficulties, a greater long-term problem may be the local deterioration of water quality caused by climate change (Figure 2), or even the disappearance of the very body of water that constitutes the tourist attraction (Figures 3–6).

Furthermore, because of extremely high summer temperatures, bathing habits are also changing radically. According to Makkos, many people now only go bathing in the afternoon in the heat, so there should be a switch to Mediterranean opening hours: closing in the afternoon and opening in the evening and at night (Turizmus.com, 2026). Such shifts in timing are one of the typical ways in which tourists adapt to climate change, alongside changing their destination or their activities (Gössling and Scott, 2026).



Figure 2. Lake Velence turned chartreuse in 2026, probably due to an algal bloom, as seen from space (*Copernicus / Sentinel-2 photos in Varga, 2026*)

At Lake Velence, the signs of drying-up due to warming were especially apparent: empty beaches and stretches of shoreline, closed snack bars, as if on a late-autumn Sunday – with one enormous difference: the thermometer showed more than 35 degrees in the shade, and in places the water had retreated several tens of metres from the shore, although even where it had not, there were few bathers in the water (Turizmus.com, 2026). My personal experience in this regard is that in April 2026 the water surface on the Velence stretch of the lakeshore already visibly began several metres away from the shore. The lake had already reached record low water levels in 2021–2022, and a climate risk assessment of Lake Velence identifies beach, bathing and angling tourism as the activities most vulnerable to climate change (Boromisza and Harea, 2023). By September 2026, water levels had remained consistently 40 cm below the previous record low of 2022, as shown by official records (Figure 3).

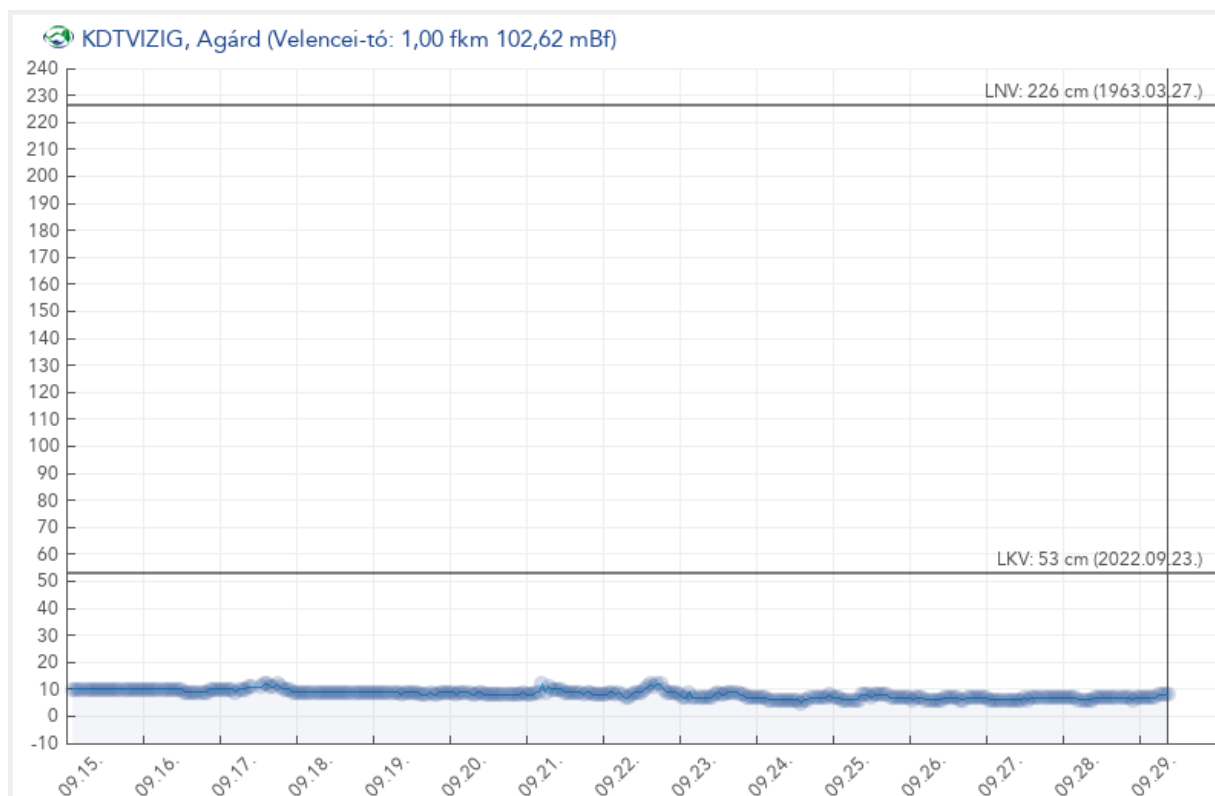


Figure 3. Water levels at Agárd, Lake Velence, in September 2026 (*Vízúgy, n.d.*)

Because of drought summers, fewer foreign and domestic guests are expected to come to Lake Balaton or Lake Velence. As Hungarian summers grow ever hotter, northern destinations such as Scandinavia are gaining in value, which also puts Hungary in a difficult position in terms of tourism (Infostart, 2026a). This is consistent with international findings that tourists are becoming increasingly flexible in their choice of destination and season, and that in the near term rising climate-related costs are likely to be the main factor shaping changes in demand (Gössling and Scott, 2026). These adaptive decisions are essentially cognitive processes: visitors increasingly rely on digital information when deciding whether, when and where to travel, which illustrates how digital tools extend human cognition in sustainability-related choices (Zöldy et al., 2022). Such information may include weather forecasts, satellite images and real-time water-level data, such as those documenting the changes at Lake Velence in this study (Figures 2 and 3).

In the case of Lake Velence, too, the greatest problem would be if the body of water that constitutes its main attraction became unsuitable for bathing or disappeared altogether (Figure 4). This is clearly supported by the research of Wirth (2017). According to his survey, the primary preference of the majority of respondents (84.41%) remained beach-going and bathing. The secondary preference, however, was not wellness (14.3%), water sports or health tourism (16.2%), but cycling (41%). Events and hiking each appealed to almost 28% of respondents, whereas visiting wineries (13.63%), fishing (12.3%), horse riding (2.6%) and other activities (5.2%) were less popular. The position of Lake Velence among Hungary's lakes as a tourist destination is faithfully reflected in the fact that 58% of respondents preferred Lake Balaton, to which the much smaller and less attractive Lake Velence (18% of mentions) cannot be a real competitor. The situation is further complicated by the fact that natural processes at the lake tend towards its lower, pre-regulation water level, whereas tourism and other economic activities depend on an artificially maintained high water level, which creates a fundamental conflict between ecological and economic interests (Boromisza and Harea, 2023).



Figure 4. Water has disappeared from parts of Lake Velence, 3 July 2026 (Photo: Zoltán Adrián, in Csóti, 2026)

Lake Balaton faces similar difficulties, although the problem is not yet as severe as in the case of Lake Velence. Because of climate change, the expected increase in the frequency of low water levels, the spread of invasive species, new forms of algal growth and increasing tourist pressure, the future state of Lake Balaton is difficult to predict. For the sake of sustainable lake use, natural habitats must be preserved, external loading reduced and adaptation to the changing climate achieved, while Lake Balaton continues to fulfil its ecological, recreational and economic role. The management of Lake Balaton is therefore the art of balancing the preservation of good ecological status with human use, which requires continuous dialogue and science-based water and land management (Erős and Vasas, 2026). Considering conditions in Hungary, this approach should be applied generally to all Hungarian lakes.



Figure 5. The shoreline of Lake Balaton has retreated by approximately 20 metres. Balatonalmádi, September 2026 (Author's photo)

Since Lake Balaton is not only a tourist destination but also a significant water resource and an important habitat, the lake should be managed in an integrated way, as a hydrological and ecological unit. However, in recent decades, and especially over the past 16 years, the preservation of Lake Balaton as an ecological unit has not been a priority.

According to Gábor Vasas, Director General of the Balaton Limnological Research Institute, Hungary's large shallow lakes (Lake Balaton, Lake Fertő, Lake Velence and Lake Tisza) are especially sensitive to the challenges posed by the weather, that is, by climate change. The summer of 2026 brought these problems into particularly sharp focus. The average water temperature of Lake Balaton, for example, has risen significantly over the past fifty years. The number of days with water temperatures above 25 °C has increased dramatically, exceeding 70 in 2026. Long-term measurements show that the warming of the lake has accelerated sharply in the last two to three decades: since 2000 its water has warmed by about 0.07 °C per year, making it about 1.7 °C warmer than at the turn of the millennium, while lake heatwaves have become more frequent and longer (Tóth and Li, 2025).

Warming also favours heat-tolerant aquatic plants with spiny leaves that are unpleasant for bathers, the spread of invasive species such as *Vallisneria spiralis*, which already occupied about 40 km of shoreline in the western basins by 2024, and a higher risk of algal blooms – all of which directly reduce the lake's appeal for bathing (Tóth and Li, 2025). Moreover, the first heatwave of 2026 and the so-called heat dome caused the water to warm to around 30 °C down to a depth of 3–4 metres. A significant problem is that most of Lake Balaton's biota lives in the littoral zone. This zone could be very rich in wildlife if it were left alone. The lack of extensive reed beds, however, is a serious problem, not only for wildlife but also for water clarity. As the lakeshore is already overdeveloped, wildlife is increasingly being displaced from its natural habitats (Világgazdaság, 2026b).



Figure 6. Alarming low water levels at Lake Balaton on 27 August 2026 (Photo: Márton Mohos, in Csóti, 2026)

Despite legal regulation, insufficient attention is paid to the ecological system of Lake Balaton. Construction along the shores often takes place at the expense of natural habitats. The shoreline at Balatonfüred, for example, has been almost entirely built up. The most important element in maintaining water clarity and the ecological balance of the lake is the preservation of the shoreline reed and bulrush communities. According to surveys of the extent of reed beds at Lake Balaton, the reed area is not shrinking; quite the contrary: between 2008 and the most recent survey in 2020, the area of reed beds outside the lakebed nearly doubled, while their total area within the lakebed has remained around 1,200 hectares, changing very little. This does not, however, represent a clear improvement: despite all the positive signs, the quality of the reed beds continues to deteriorate. Furthermore, the construction of numerous blocks of flats and holiday estates is harmful not only because it destroys natural assets; sooner or later, those who like to visit Lake Balaton may also lose the familiar and much-loved scenery, which is one of the main tourist attractions of Lake Balaton and its surroundings (Kun, 2022).

Apart from the ecological factors already mentioned, economic problems are also a significant driver of the decline in tourism. In 2026, attendance at paid beaches in Siófok fell markedly. For example, almost one in five visitors disappeared from the Nagystrand (Main Beach) in Siófok, as people are now economising even on beach admission at Lake Balaton. Róbert Lengyel, Mayor of Siófok, reported that visitor numbers at the Siófok Nagystrand had fallen by around 20 per cent, while a decline of about 10 per cent had been measured at the paid beach in Sóstó. As a result, the beaches operated by Balaton-Parti Kft. may have lost approximately HUF 70 million in ticket revenue (Világgazdaság, 2026a).

For Lake Balaton and its region to survive both as a natural ecological unit and as a tourist attraction, sustainable lake management, settlement development and tourism development must be established. Since the main objective of sustainable tourism development is to strike a balance between meeting tourism demand and preserving the region's ecological assets (Gyurkó and Csegődi, 2024), the current comprador-type land use is entirely unsustainable. International experience shows, however, that although knowledge about the effects of climate change on tourism is available, its translation into action at destination level is often hindered by imprecise concepts, misaligned levels of governance and competing stakeholder priorities (Hübner and Ioannides, 2026). From the perspective of cognitive sustainability, this knowledge-to-action gap is itself a cognitive challenge: sustainable lake use depends not only on regulation but also on how local stakeholders, decision-



makers and visitors perceive, interpret and act upon the available knowledge about environmental change (Zöldy et al., 2022).

What regulatory instruments could facilitate sustainable lake management?

- Environmental regulations: these can limit pollution, protect local wildlife and regulate the use of natural resources.
- Spatial development regulations: these can steer the development of tourism infrastructure, protect the landscape and restrict building density.
- Tourism regulations: these can encourage sustainable tourism practices, limit mass tourism and promote the development of the local economy.

4. Conclusion

In this study I have examined the relationship between climate change, anthropogenic pressure and tourism through the example of Hungarian lakeside tourist destinations, primarily Lake Balaton and Lake Velence. The relevance of the research lies in the fact that the heatwaves, periods of drought, extreme precipitation events and rising water temperatures that are becoming increasingly frequent as a result of climate change directly threaten the natural foundations of recreational tourism based on bodies of water. These processes are further intensified by the development of shoreline areas, habitat fragmentation, the growing burden of tourism infrastructure and anthropogenic impacts on water quality.

In the case of Lake Balaton, and Lake Velence in particular, the state of the water body fundamentally determines the tourist appeal of the destination. Falling water levels, warming water, deteriorating ecological status and the transformation of shoreline habitats therefore represent not only an environmental risk but also a significant economic and tourism risk. At the same time, tourism demand is not influenced by environmental change alone: the economic environment, prices and the growing attractiveness of foreign destinations are also significant factors.

In order to preserve the tourist appeal of wetland areas, sustainable lake management, the preservation of natural shoreline habitats and reed beds, the restriction of construction, and the adaptation of tourism infrastructure to climate change are of paramount importance. In addition, the tourism offer needs to be diversified so that destinations depend less exclusively on bathing and the summer season. Sustainable development requires coordinated environmental, spatial development and tourism policy regulation that simultaneously ensures the preservation of natural resources, the viability of the local economy and the long-term adaptive capacity of tourism. Strengthening the cognitive dimension of sustainability – environmental awareness, access to reliable information and the capacity of local communities and visitors to learn and adapt – is therefore an essential condition for the long-term resilience of lakeside destinations. As the study relies on secondary data and a single tourist season, further research based on primary visitor surveys and longer time series is needed to quantify the relative weight of climatic and economic factors in the decline of lakeside tourism.

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