

A GIS-Based Investment Model for Regional H₂ Generation Potential Assessment with an exemplary application

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Abstract— Electricity-based green hydrogen is considered a potential key element in the defossilization of global energy systems. As a secondary energy carrier it is intended to be used as a fuel in energy sectors where direct electrification is not feasible, as well as for electricity generation to complement volatile renewable energies. Although the demand is significant and the potential applications are diverse, both availability and cost are subject to considerable uncertainty. In particular, the availability of renewable energy, which in turn depends on site conditions, land availability and the availability of water, are important for the viable operation of electrolyzers and thus for the estimation of local H₂ production capacities. This study presents an approach that allows for the calculation of cost potential curves on a global scale with high spatial resolution - with the exemplary application to Iberian Peninsula (IPN). The proposed investment model includes a GIS analysis of renewable energy land availability at 1° x 1° grid resolution and capacity factor time series generated using Renewables.ninja. Finally, the model determines the optimal contribution of different volatile, renewable energy technologies, taking country-specific WACC estimates into account.

Index Terms— Hydrogen, Renewable energy sources, Optimization models, Power system economics

NOMENCLATURE

Sets

n	Countries
r	Technologies (PV, Wind, H ₂)
t	Time
x	Capacity share segments
z	Tiles
z_{desal}	Tiles allowing desalination

Parameters

a_n	Annuities (country specific)
$\alpha_{n,r,t,z}^{RE}$	Capacity factor time-series
c_r^{cap}	Capital Costs RE [€/GW]
$K_{n,r,z}^{max}$	Max. Capacity per tile per country [GW]
χ_x^{yShare}	Share of H ₂ production capacities

f_{H2}	Hydrogen calorific value [kWh/kg]
$y_{n,r,t,z}^{ub}$	Total energy production per tiles per timestep [GW]
η_{h2}	Electrolyzer efficiency [-]
<i>Variables</i>	
C^{tot}	Total costs (objective function) [€]
C_r^{cap}	Capital costs [€]
C_{desal}^{cap}	Capital costs desalination [€]
$K_{n,r,x,z}$	Invested Capacities [GW]
$y_{n,r,t,x,z}$	Total energy production [GW]

I. INTRODUCTION AND LITERATURE REVIEW

The transition towards a decarbonized energy system requires investment decisions in low-carbon technologies to meet emission reduction goals, including renewable energy, electrification of end-use sectors, energy efficiency, and low-carbon fuels [1–3]. However, the viability of these investments remains uncertain due to significant uncertainty regarding technological advancements, infrastructure developments, and cost trends in the coming years. In particular, hydrogen and its derivatives are expected to play a crucial role, with green hydrogen from renewable sources considered the primary pathway for hydrogen production. As the investment costs of renewables are expected to decline, hydrogen production from renewable energy sources is becoming increasingly competitive [3]. With Europe anticipating high import volumes due to hard-to-abate emissions and limited renewable energy potential, it is essential to determine the trade-off between hydrogen imports and the expansion of domestic production capacity—based on cost considerations and available land area.

The data-driven analysis of green hydrogen production has been explored in several studies, each with different regional perspectives. Hydrogen production potentials on a global scale have been investigated by [4–6] using optimization models. [4] present a model that calculates the cost of producing hydrogen from different sources. [5] propose a

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comprehensive model that allows for different system configurations. Based on this, costs and production capacities are estimated. [6] present a model that determines hydrogen production costs and capacities for all countries except those in the European Economic Area, covering 14 different H₂ production pathways.

Other studies focus on a pre-selection of countries with favorable conditions for renewable energy production and significant export potential [7,8]. [7] present a cost-potential model for 28 countries, including the necessary transport infrastructure. Their results indicate a production potential of 79 PWh/a in these countries at costs below €2.30/kg. Models for estimating the hydrogen production potential within Europe or in Europe and neighboring regions such as MENA have been presented by [8–11]. [8] describe a model for calculating the levelized cost of hydrogen (LCOH) for 30 European countries. The work of [9,10] provides supply curves for European countries as well as supply curves for the MENA region, including transport costs to Europe. [11] analyze import costs and potential volumes of green hydrogen transported to Germany from different European and MENA regions, taking into account not only hydrogen production but also factors such as local H₂ demand, storage and pipeline transport costs.

These studies differ in two key aspects: first, in the data sources used to assess renewable energy potentials. Most studies use hourly resolution technology specific capacity factor datasets and available land area estimations. Time series are often derived from MERRA-2 or ERA5 datasets ([4,7,8] respectively [9–11]). The estimation of the eligible area is done either by GIS-based analysis or by applying land use factors, expressed, for example, as a percentage of the total land area of a country. Prior to optimization, the high resolution of meteorological and land-use data is reduced using aggregation or other clustering methods. Secondly, studies differ in whether hydrogen production potentials are integrated into off-grid systems for hydrogen or hydrogen derivative production [5,6,10], or into systems focused on transport infrastructure [7,10,11].

As production potentials and costs are presented on national level in all cases presented above, a knowledge gap remains regarding a detailed assessment of hydrogen production costs that integrates a global scale with high spatial resolution. This study addresses this gap by combining a detailed spatial analysis with an investment model. Based on this analysis, H₂ cost-potential curves are derived. The study considers off-grid scenarios for ground-mounted PV, onshore, and offshore wind technologies at a spatial resolution of 1° × 1°, incorporating exclusion criteria such as water scarcity. The remainder of this paper is structured as follows: The methodology regarding renewable energy profiles and land eligibility as well as the investment model for the assessment of hydrogen production potentials are presented in Section 2. In section 3, the specifications of the case study are stated and its results are discussed in the subsequent Section 4. In the last Section 5, the findings of the paper are summarized.

II. METHODOLOGY

A. Renewable Availability Profiles

The renewable energy capacity factor time series have been generated using the Renewables.ninja tool, which provides simulated wind and PV power outputs based on historical climate data [12,13].

Renewables.ninja utilizes the MERRA-2 reanalysis dataset to estimate wind speeds at typical hub heights, applying a logarithmic wind profile and standardized power curves to calculate capacity factors [12]. For solar energy, it leverages MERRA-2 irradiance and temperature data, incorporating system efficiency models to determine PV output [13]. The dataset for this study is constructed at a spatial resolution of 1° × 1°, with the centroid of each grid cell serving as the reference coordinate for time-series generation. The resulting hourly time series provide renewable availability profiles for each grid cell.

B. Land Eligibility

To identify areas that are suitable for green hydrogen production, a land eligibility analysis has been conducted. This study focuses on dedicated (off-grid) systems where hydrogen is produced via electrolysis powered by nearby renewable energy sources. Considered renewable energy sources are onshore and offshore wind and utility-scale PV. For each respective technology, eligible land areas are identified based on exclusion criteria. Furthermore, areas with high water scarcity are deemed unsuitable for the production of green hydrogen. For each spatial tile, the available area for each respective technology is determined and multiplied with a power density based on the study [14] to assign a cap on the maximum installable capacity in this cell. In the following, the exclusion criteria for each technology and water scarcity are described.

The eligible areas for utility-scale PV are based on the dataset [15]. Areas were excluded based on topographical, hydrological, ecological, and socio-economic constraints. Specifically, complex terrain with significant elevation variations, permanent surface waters, and dense forests with over 50% tree cover were considered unsuitable. Additionally, remote and uninhabited areas lacking infrastructure or demand, densely urbanized regions (>50% urbanization), protected areas, and cropland were excluded to preserve ecological integrity and minimize land-use conflicts. For land eligibility of onshore wind energy, a geodata set based on the exclusion criteria defined in [16] was created. Exclusions were based on environmental protection, topographical constraints, and land cover suitability. Protected areas, steep slopes (>20%), high altitudes (>2000m), densely urbanized areas, water bodies and permanently flooded or snow-covered lands were considered unsuitable. To identify suitable areas for offshore wind energy, the dataset described in [17] was utilized. The dataset defines eligibility based on wind speeds exceeding 7 m/s, water depths of up to 50 m for fixed foundations or 50–1,000 m for floating foundations, and a minimum contiguous area of 10 km², all restricted to each country's exclusive economic zone.

To identify areas with constraints in water availability for electrolysis, the WRI Aqueduct dataset [18] was used. Areas classified under the "Baseline Water Stress" indicator as "Extremely High," "Arid and Low Water Use," or "High" were deemed ineligible due to insufficient renewable surface and groundwater supplies, with the exception of coastal areas where we assume desalination capabilities. The remaining space is available for capacity expansion. The maximum expansion capacity is calculated based on area and power densities as described in [14].

$$K_{r,z}^{max} = A_{r,z} \cdot x_r \quad (1)$$

C. Investment Model

The model is a Python-based investment optimization model designed to allocate investments in renewable energy capacity and hydrogen production capacity. It operates on the basis of preliminarily identified regionally disaggregated maximum capacities and capacity factor time series. The model considers photovoltaic (PV), onshore wind and offshore wind technologies for capacity expansion, while the hydrogen production is achieved exclusively through electrolyzers. Furthermore, hydrogen production capacity can also be invested in areas where water is scarce but desalination plants can be operated.

The model is formulated as a linear program, key equations are summarized subsequently. The objective function (2) minimizes the investment costs for renewable energy and hydrogen production capacities. Equations (3), (4), and (5) describe the annualized investment costs for the different technological options. Equation (6) defines the capacity constraints for renewable energy and equation the capacity constraint on hydrogen production. The maximum amount of hydrogen that can be generated within each tile using renewable energy capacities is calculated in Equation (8) and then spatially and temporarily aggregated in Equation (9). Here, the required share of the potential hydrogen production acts as a lower bound and is expressed in discrete percentages of renewable energy production capacities. This parameter is calculated in (10), (11) and (13) using the renewable capacities and capacity factor time series determined in sections IIIA and IIB. The parameter X_y^{Share} divides the total production capacity into 5 equidistant sections, enabling an analysis of the marginal production cost if not all of the energy potentially supplied by renewable energy sources is used for hydrogen production (12). After the optimization, the (marginal) hydrogen production costs per segment are determined by dividing the corresponding increase in the objective function value of the section by the corresponding increase in hydrogen production.

$$\text{minimize! } C_x^{tot} = C_x^{cap} + C_{H2,x}^{cap} + C_{H2,x,desal}^{cap} \quad (2)$$

$$C_x^{cap} = \sum_{r,z} a_n \cdot K_{r,x,z} \cdot C_r^{cap} \quad (3)$$

$$C_{H2,x}^{cap} = a_n \cdot K_{H2,x} \cdot c_{H2}^{cap} \quad (4)$$

$$C_{H2,x,desal}^{cap} = a_n \cdot \sum_{z_{desal}} K_{H2,x,z_{desal}} \cdot c_{H2}^{cap} \cdot x_{desal} \quad (5)$$

$$s. t. \quad K_{r,x,z} \leq K_{r,z}^{max} \quad (6)$$

$$y_{H2,t,x,z} \leq K_{H2,x,z} \quad (7)$$

$$y_{H2,t,x,z} \leq \sum_r (\alpha_{r,t,z}^{RE} \cdot K_{r,x,z}) \cdot \eta_{H2} \quad (8)$$

$$\sum_{t,z} y_{H2,t,x,z} \geq y_{H2,x}^{pot} \quad (9)$$

$$y_{r,t,z}^{ub} = \alpha_{r,t,z}^{RE} \cdot K_{r,z}^{max} \quad (10)$$

$$y_{H2}^{max} = \sum_{r,t,z} y_{r,t,z}^{ub} \cdot \eta_{H2} \quad (11)$$

$$X_y^{Share} = [0.2, 0.4, 0.6, 0.8, 1.0] \quad (12)$$

$$y_{H2,x}^{pot} = X_y^{Share} \cdot y_{H2}^{max} \quad (13)$$

Postprocessing

$$\overline{c_{H2,\Delta x}} = \frac{C_x^{tot} - C_{x-1}^{tot}}{\sum_{t,z} (y_{h2,t,x,z} - y_{h2,t,x-1,z}) \cdot \Delta t} \cdot f_{H2} \quad (14)$$

III. APPLICATION CASE AND DATA

In this study, the investment model is applied to Spain and Portugal as an exemplary case study to compute cost potential curves for projected hydrogen production potentials. Thereby subsequently intermediate results regarding regionally differentiated potentials of photovoltaic (PV), onshore wind, and offshore wind technologies are presented. Specifically the case study investigates to what extent a preselection of the most attractive renewable sites within a region (similarly to the approach in [7,8]) affects the results.

To analyze the regional distribution of hydrogen production sites within the peninsula with different renewable energy conditions, the dataset for each of the three technologies is clustered into three classes according to their full load hours: the best 10% of all locations, the mid 40%, and the remaining sites. As overseas territories are neglected, a total of 52 tiles for PV and wind are allocated to mainland Spain and Portugal, and 41 tiles for offshore wind. For PVs and onshore wind, the three clusters comprise 5, 21 and 26 tiles respectively, and 4, 16 and 21 tiles for offshore wind. Note that by reducing the number of tiles being examined after clustering, the lower bound of the hydrogen energy to be generated in equation (9) is also reduced and the resulting potential curves are covering less potentials. The key parameters for cost analysis in the model are based on [19,20] and are listed in Table 1 together with key statistical indicators for the capacity factor time series. Here annual full load hours, corresponding to the sum of hourly capacity factors are displayed.

Description		Unit	Value
CAPEX – PV		€/kW	540
CAPEX – Wind (onshore)		€/kW	1240
CAPEX – Wind (offshore)		€/kW	2400
CAPEX – Electrolyzer		€/kW	1150
Efficiency – Electrolyzer		-	70 %
Conversion factor – Hydrogen		kWh/kg	33
WACC IPN		-	0.038
Lifetime PV		a	30
Lifetime Wind (onshore)		a	25
Lifetime Wind (offshore)		a	25
Capacity Factor statistics (full load hours):			
IPN	PV	Wind	Wind (offshore)
Mean [h]	1577.8	2383.0	3257.7
Standard Deviation	110.5	538.3	786.2
Min(top10)	1729.9	3136.2	4493.5
Min(mid40)	1598.4	2378.9	3139.4
Min(rest)	1378.0	1357.1	1691.2

Table 1: Investment costs and capacity factor analysis

IV. RESULTS AND DISCUSSION

A. Spatial distribution of pre-selected renewable energy sites with high full load hour values

The following analyses illustrate the spatial distribution of renewable electricity generation suitable for hydrogen production, focusing on local sites not suffering from water availability constraints. These are grouped into the best 10 %, mid 40 % and lowest 50 % of onshore wind sites and PV in Figure 1 and Figure 2, respectively. Figure 1 also shows sites with offshore wind potentials as hatched areas. As expected, the locations with favorable conditions for PV generation are quite different from those for wind technologies. While the sites with especially high full load hours for wind technologies are distributed across the peninsula, the corresponding regions for PV are more concentrated in the South, the South-East and Mallorca. These locations correspond to favorable locations in [21–23]. The optimization results for the top 10% of each technology reveal that onshore wind power capacity can reach a maximum investment of 42.21 GW, while offshore wind can expand up to 36.37 GW. In contrast, PV expansion is limited to 23.30 GW, likely due to geographical constraints and the limited spatial availability within these tiles. Therefore, although the solar radiation is high, the resulting hydrogen production capacity is expected to be small.

The statistical indicators in Table 1 show that the average full-load hours for (onshore and offshore) wind diverge substantially between regions, whereas the variations for PV are considerably lower. At the same time the average full load hours for wind at good sites exceed by far the corresponding values for PV.

B. Assessment of hydrogen production capacities

Figure 3 shows the cost potential curves for the Iberian peninsula for the three clusters as well as for the total expansion potential.

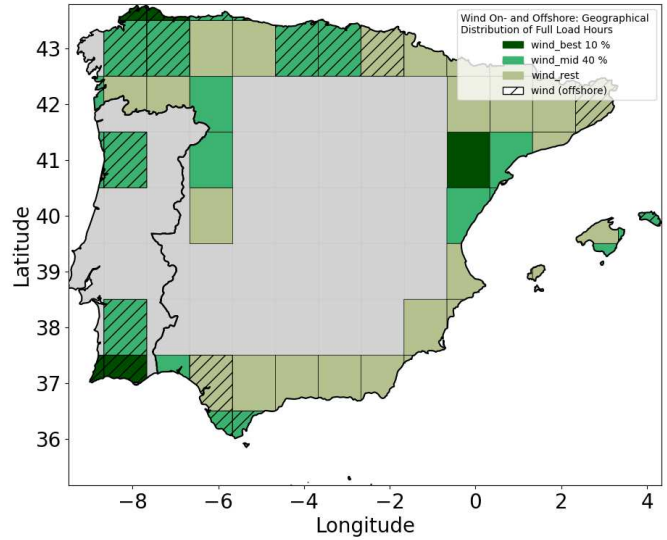


Figure 1: Spatial distribution of full-load hours for onshore and offshore wind energy, along with a color representation of the cluster assignment.

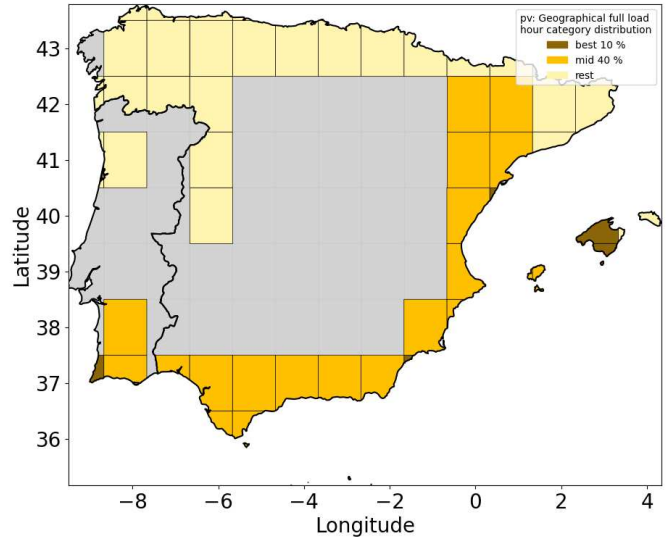


Figure 2: Spatial distribution of full-load hours for PV energy, along with a color representation of the cluster assignment.

The sections (datapoints) of the curves reflect the equidistant expansion shares defined by X_y^{Share} . The results show that based on the most promising sites, an expansion of hydrogen production up to 574 TWh is possible, with costs remaining below 2 €/kg. The middle and lower clusters achieve maximum expansion capacities of 2028 TWh and 2378 TWh respectively, with costs ranging from 1.9 €/kg to 2.15 €/kg and 2.1 €/kg to 2.68 €/kg respectively.

Based on these findings, two key observations emerge. First, the cost curves for the 10% and 40% clusters intersect. Notably, the total investment costs required to fully develop the 10% cluster potential is higher than the costs for the 40% cluster up to a capacity share of 60%. This discrepancy is due to the fact that the selection of tiles is done separately based on their potential for the different renewable energy sources. As a result, the 10% cluster may include sites where the combined potentials are lower than for the best tiles/sites in

the 40% cluster. This shows that a preselection based on resource potentials differentiated by resource types may lead to inefficient results. The inefficiency is also evidenced by the fact that the cost potential curve based on all tiles provides higher potentials at the same cost, than the aggregation of the three individual curves. On the other hand, the results based on all tiles may be biased downwards since the sections considered are rather large, and the marginal costs are approximated by finite differences between these sections.

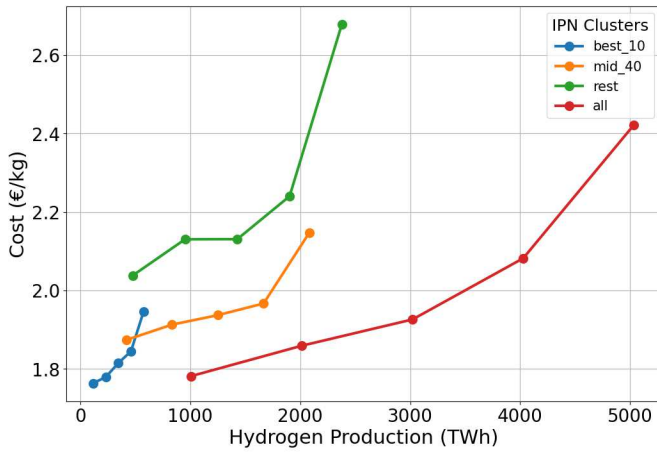


Figure 3: Cost potential curves for Spanish hydrogen production and different pre-optimization clusters, taking into account all technology options

Secondly, the total potential for capacity expansion of hydrogen appears is limited by the widespread exclusion of tiles in the center of Spain and on the west coast of Portugal due to water scarcity. This limits the hydrogen potential to 5,000 TWh. At the same time, the cost curve covers a price range between 1.78 €/kg and 2.42 €/kg, which is rather low in relation to current price quotes. This is mostly driven by the investment cost estimates which reflect future mature technologies.

For two of these cost potential curves, Figures 4 and 5 indicate the geographical distribution of the used sites along the expansion path. The mapping to the tile areas is done for the best 10 % cluster (blue) and the total expansion potential (red). The decreasing color saturation in the maps corresponds to production cost increases in Figure 3. Inspection shows that those regions with the highest number of full load hours – being part of the top 10% cluster – in many cases tend to be most attractive for investment when the whole expansion potential is available. Specifically, investments in production capacities are primarily made along the eastern Mediterranean coast as well as the northern and southern Atlantic coasts, which aligns with the favorable locations shown in Figures 1 and 2. An exception is the highlighted tile in Figure 4, which belongs to the 10% cluster but is only invested in relatively late, at prices exceeding 2.1 €/kg, in the case where all available tiles are considered. Here, the potentials of wind and PV are with 0.5 GW and 5.22 GW very limited. But with offshore wind potentials and

capacities being very high with 36.4 GW, investments in hydrogen capacity are rather costly.

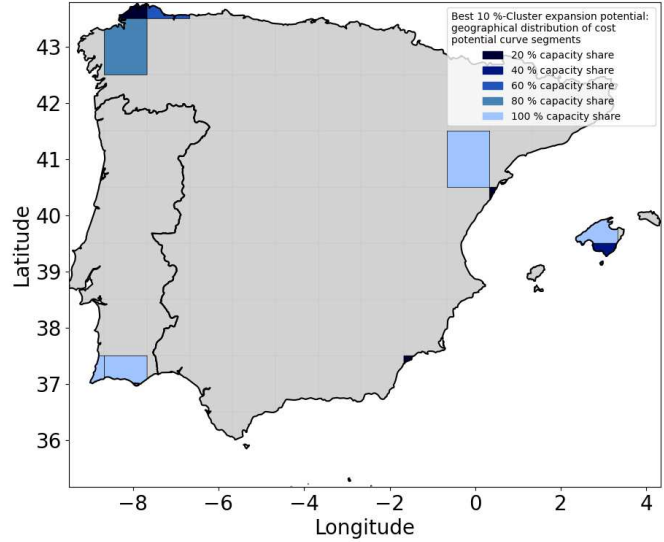


Figure 4: Spatial distribution of the best 10 % locations of maximum expansion capacities for green hydrogen

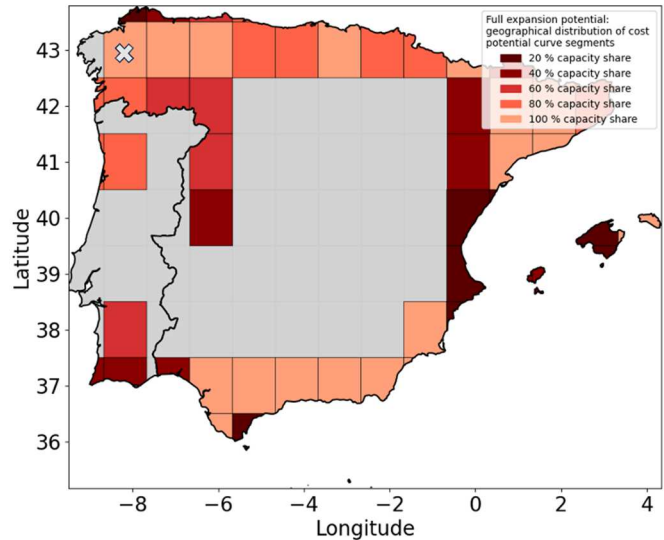


Figure 5: Spatial distribution of locations of maximum expansion capacities for green hydrogen covering all clusters

V. CONCLUSION

On the one hand, the results show that early clustering leads to differences in hydrogen production costs and production potential, with the maximum production capacity limited to less than 600 TWh for the most favorable sites alone. Also, locations with shared potentials lead to low production costs which may be overlooked when clustering is done on a single technology basis. For the Iberian peninsula as for other parts of the world, limitations in water supply turn furthermore out to be very relevant and have to be considered in any analysis.

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