HELMo Gramme

Denmark 2045

A Calculation-Backed Strategic Plan
for Full Decarbonisation

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Abstract

This report proposes a calculation-backed strategic plan for Denmark to achieve full decarbonisation by 2045. Using MacKay's kWh/person/day framework, we estimate current gross energy demand at approximately 133 kWh/p/d, including domestic uses and the embodied energy of imports. The plan reduces demand to approximately 101 kWh/p/d through heat-pump electrification, electric vehicles, industrial efficiency gains and lower fossil conversion losses.

Domestic low-carbon supply reaches approximately 103 kWh/p/d through a diversified portfolio combining offshore wind, onshore repowering, solar PV, biomass and biogas phase-down, Power-to-X, interconnectors and battery flexibility. Offshore wind also creates an export surplus, shifting Denmark from a net energy importer to a clean-energy exporter and technology hub. With an estimated investment of ≈€90 billion over 20 years, the plan remains fiscally credible and positions the energy transition as both a climate pathway and an industrial strategy.

1 Introduction

Denmark invented modern wind power. The country built the world's first offshore wind farm in 1991 [2], pioneered cooperative ownership models that gave citizens a direct stake in the transition [53], and by 2024, 63.1% of its electricity came from wind (≈57%) and solar (≈6%) [11, 2]. With 65% of households connected to district heating [3], a Climate Act mandating net-zero by 2045 [4], and an AAA-rated sovereign balance sheet, Denmark is routinely presented as the country that has already solved the energy transition.

It has not. Electricity is only part of the story. When heating, transport, industry, and the embodied energy of imported goods are included, our bottom-up analysis estimates Denmark's *total* gross energy demand at ≈133 kWh/p/d. Renewables covered only 30% of actual consumption in 2023 [11]. More than half of Denmark's energy system still runs on fossil fuels.

The fragility of the current trajectory was exposed in December 2024, when an offshore wind tender for 6 GW received zero bids [5]. The failure forced a policy pivot to Contracts for Difference and raised a harder question: can Denmark's renewable endowment, combined with credible demand reduction, close not just the electricity gap but the full consumption-based energy balance by 2045? This paper proposes a quantified answer.

2 Method

All figures are expressed in **kWh per person per day** (kWh/p/d). For a population $n = 5{,}993{,}000$ [25]:

$$E_{\mathrm{p/d}} = \frac{E_{\text{national}}\ [\mathrm{kWh/yr}]}{n \times 365} \tag{1}$$

Demand is built bottom-up across eight sectors (HVAC, cars, planes, food & farming, gadgets, lighting, stuff, public services) using MacKay's methodology [1] adapted for Denmark's climate, transport patterns, and economy.

Supply is calculated either from installed capacity and load factors, where GW targets are used (offshore wind, Power-to-X), or from MacKay-style territorial coverage assumptions for onshore wind and solar PV (see Annex K for full derivation). For GW-based technologies, the conversion to kWh/p/d is:

$$E_{\mathrm{p/d}} = \frac{P_{\mathrm{GW}} \times \mathrm{LF} \times 8760 \times 10^6}{n \times 365} \tag{2}$$

As a reference, 1 GW of offshore wind at Danish load factors delivers ≈1.6 kWh/p/d; the plan's 35 GW target is therefore a 14-fold scale-up from today's 2.5 GW.

3 Results and Discussion

3.1 Demand

Table 1 summarises our bottom-up demand estimates. Our total of ≈133 kWh/p/d is higher than the Danish Energy Agency's (DEA) reported ≈89 kWh/p/d [2]. This is not a direct sector-by-sector disagreement. The DEA reports territorial energy consumption, while our estimate follows MacKay's lifestyle-based framework. These categories do not map one-to-one onto DEA statistical sectors.

The main difference is the broader consumption-based boundary: domestic agriculture and industry are partly included in DEA data, but the embodied energy of imported goods and outsourced production is not fully captured.

Table 1: Current demand by sector (kWh/p/d)

Sector	kWh/p/d
HVAC (heating/cooling)	28.5
Cars	11.3
Planes	8.0
Food & Farming	10.3
Gadgets & Appliances	3.9
Lighting	1.0
Stuff (manufacturing)	68.0
Public Services	2.3
Total demand	**≈133**

We target a **24% demand reduction to ≈101 kWh/p/d by 2045**. The largest lever is heating: Denmark's DH network enables replacing gas boilers with heat pumps at COP 3–4, cutting HVAC by 10 kWh/p/d (Annex D). Transport follows: full EV penetration by 2035 and the Fehmarn Belt rail link (which replaces short-haul Copenhagen–Hamburg flights, the busiest short-haul air route between Denmark and Germany at ≈8 daily nonstop flights, with a 2.5-hour electrified train) save 7 kWh/p/d. Industry contributes −5 through low-temperature electrification; appliances/lighting save −3 via EU

Ecodesign and LED. The remaining −7 comes from system efficiency: when fossil conversion losses disappear, primary-energy requirements drop even without behavioural change. This is conservative vs. the ≈29% IDA pathway [6].

3.2 Supply: From Theoretical Ceiling to Credible Plan

MacKay's framework provides a powerful way to estimate Denmark's renewable potential from physical assumptions: land or sea coverage, power density, efficiency and load factors. However, these estimates should be read as technical potentials, not automatically deployable capacity. In practice, actual renewable production remains only ≈ 40 kWh/p/d, because deployment is constrained by land use, social acceptance, grid capacity, permitting and financing. Our plan therefore uses the MacKay results as a starting point, but retains only the resources that can credibly be built, integrated and scaled by 2045.

Table 2 presents the supply analysis. Current renewable production is sourced from the DEA [2]. The "Plan" column shows the domestic allocation of each technology. Offshore wind and PtX are computed from GW targets using Eq. 2; onshore wind and solar PV are computed from territorial coverage assumptions following the Excel workbook methodology (see Annex K for full derivation).

Table 2: Renewable supply plan (kWh/p/d)

Source	Current	Plan	Deployment
Offshore wind	4.5	**28.0**†	35 GW × LF 39.6%
Onshore wind	5.0	**12.0**	2.5% territory
Solar PV	1.6	**15.0**	Rooftop + 0.5% farm
Biomass/Biogas	26.7	**18.0**	See below
Wave & Tidal	0	**5.0**	Excel estimate
Geothermal	<0.1	**2.0**	DH baseload
Hydro (DK mainland)	<0.1	**0.1**	Micro-hydro
Subtotal	≈38	80.1	
Power-to-X (mainland)	0	10.0	10 GW electrolysers
Greenland hydro-PtX	0	**1.5**	See Pillar 4b
Grid, storage & balancing	≈2	11.0	11 GW interco. + batteries
Total	**≈40**	**≈102.6**	

Note: †Offshore wind total output is 55.5 kWh/p/d; 28.0 serves domestic demand and 27.5 is exported. PtX electrolysers (10 kWh/p/d net) are powered by system-wide renewable surplus during high-production hours and do not reduce the offshore export allocation (see Pillar 4). Battery storage (Li-ion, 4h) is included in the grid envelope for intra-day flexibility.

Accounting convention. Grid imports are treated as balancing flows from neighbouring low-carbon systems (Norwegian hydro, Swedish nuclear/wind), not as domestic renewable generation. Denmark's green-export claim refers to its *net annual* position: exported electricity and PtX fuels come from domestic surplus, while imports provide balancing support during low-wind or high-demand hours.

The plan is structured around **five pillars**, each addressing a distinct layer of the energy system. The logic runs from generation to conversion to system stability: first, produce massively from wind and solar (Pillars 1–2); second, electrify heat to slash the largest single demand sector (Pillar 3); third, convert the surplus into storable molecular fuels for sectors that cannot be electrified (Pillar 4); and finally, knit the system together through interconnectors and storage (Pillar 5).

1) Wind (40 kWh/p/d domestic: 28 offshore + 12 onshore).

Offshore: Denmark's offshore strategy is not limited to the North Sea. The Baltic Sea already hosts important assets and projects, including Kriegers Flak and the planned Bornholm Energy Island. However, the North Sea is the main scale-up zone: it combines larger available sea areas, stronger wind resources, shallow-water bathymetry, and direct export potential towards Germany, the Netherlands and the UK. The Danish EEZ covers ≈105,000 km^2, with North Sea water depths increasing gradually to ≈50 m over 80–100 km from the coast [52, 47]. Existing farms operate at 6–19 m depth, 14–44 km from shore [36]; the planned North Sea Energy Island hub sits at 26–27 m, ≈80 km offshore [47]. These shallow depths allow proven monopile foundations, the most cost-effective offshore typology [13]. Hub-height wind speeds of 9–10 m/s yield capacity factors of 39–45% [2, 13]. At LF = 39.6%, 35 GW yields 55.5 kWh/p/d, of which **28 kWh/p/d is allocated domestically** and 27.5 kWh/p/d is **exported**, generating €4–7B/yr [48]. The full offshore project pipeline is detailed in Annex C.

Onshore: adds 12 kWh/p/d from 2.5% territorial coverage. Denmark currently has ≈4.8 GW installed [2] delivering ≈5 kWh/p/d at 6.47 m/s average wind speed. The plan relies mainly on repowering: modern 4–7 MW turbines replacing sub-2 MW units on already permitted sites [13]. Public acceptance is supported by Denmark's co-operative tradition: in 2016, 52% of installed wind capacity was citizen-owned, and the 2008 Renewable Energy Act requires 20% local ownership of new projects [53].

2) Solar PV (≈15 kWh/p/d). Denmark's solar market has tripled from 1.1 GW_p in 2020 to over 4 GW_p in 2024 [54], with utility-scale agri-solar projects (e.g. the 215 MW Lidsø park in Lolland) driving growth. The NECP targets 20 GW_p by 2030 [54]. Rooftop PV targets 10 m^2/person at 20% *panel* efficiency (5.5 kWh/p/d); agri-PV covers 0.5% of territory at 10% *system* efficiency (9.8 kWh/p/d). The distinction matters: panel efficiency (20–24% for modern modules [13]) is the cell-level rate, while system efficiency (≈10%) includes spacing, inverter losses, and the ground-coverage ratio of elevated panels under which crops grow [37].

3) Heat revolution (−10 kWh/p/d from HVAC). Danish district heating (DH) serves 65% of households [3] through a network of hot-water pipes connecting centralised plants to buildings. Today, DH is fuelled by a mix of natural gas (≈15%), biomass/waste incineration (≈50%), and a growing share of large-scale heat pumps and electric boilers (≈35%) [33, 3], with electricity-based capacity already at 2.6 GW and targeting 6.0 GW by 2035 [33]. Large-scale heat pumps (COP 3–4 [15]) extract heat from seawater, wastewater or ambient air; a single industrial unit can serve thousands of households. This is complemented by individual heat pumps for the ≈400,000 remaining gas-heated homes [3] and deep renovation at 3%/yr aligned with EU Renovation Wave targets [23] (see Annex D).

4) Power-to-X and energy storage. 10 GW of electrolysers produce green hydrogen for **shipping, industry, and SAF** (Annex H). PtX is not treated as continuous electricity demand, but as a flexible use of surplus renewable electricity. Even without the 27.5 kWh/p/d offshore-wind export allocation, the domestic system is sized to cover Denmark's direct electrified demand, estimated at roughly 70–75 kWh/p/d after electrification.

At around 4,000 equivalent full-load hours per year, the electrolyser fleet requires approximately 40 TWh/yr of electricity input, or ≈18 kWh/p/d on an annual-average basis. After 65% electrolyser efficiency and downstream losses, this delivers ≈10 kWh/p/d of net usable molecular fuels. PtX therefore converts surplus electricity into fuels for sectors that cannot be directly electrified.

Batteries provide the short-duration flexibility layer within the grid envelope. Li-ion battery parks are modelled with a 2–4h energy-to-power ratio, consistent with grid-scale systems designed for frequency regulation, wind-ramp smoothing, solar peak shifting, and evening-demand support. Their role is therefore not seasonal storage, but high-cycling operational flexibility: absorbing surplus electricity during high-production periods and releasing it when demand, grid constraints, or price signals require it. They can contribute to daily balancing, but multi-day Dunkelflaute resilience remains covered by interconnectors, dispatchable biomass/biogas, and PtX.

4b) Greenland hydro-PtX (≈1.5 kWh/p/d, from 2035). Greenland already generates 80% of its electricity from hydropower, and its West Greenland hydropower potential is estimated at up to 20,000 GWh/yr, including more than 7,000 GWh/yr around Tasersiaq [55]. The Buksefjord expansion near Nuuk will add surplus capacity from 2032, making continuous electrolysis and tanker-exported green hydrogen or ammonia a credible Kingdom-wide complement to Denmark's domestic renewable build-out. A direct HVDC cable to Denmark (≈3,500 km) exceeds current submarine cable technology; however, Greenland's dispatchable hydro is ideally suited to continuous electrolyser operation, producing green hydrogen or ammonia for export by tanker to Esbjerg. At 5,000 GWh/yr of hydro input, 65% electrolyser efficiency and ≈85% transport yield, this delivers ≈1.5 kWh/p/d to the Danish system. A 2025 Danish–Greenlandic business initiative has proposed $6B in sustainable investments including expanded hydro and PtX infrastructure [56].

5) Grid integration and balancing imports (11 kWh/p/d). Interconnectors to Norway, Sweden, Germany, and the UK provide access to complementary low-carbon resources. These imports are not counted as domestic renewable generation; they provide adequacy during low-wind or high-demand hours, while Denmark remains a net annual exporter. During *Dunkelflaute* episodes (multi-day periods of simultaneous low wind and solar), the combination of interconnector imports (≈11 GW capacity), dispatchable biomass (18 kWh/p/d baseload), and battery reserves ensures system adequacy without fossil backup. Annex I details the interconnector portfolio.

Biomass and biogas: a controlled phase-down. Current Danish bioenergy use (≈26.7 kWh/p/d) relies on three sources: imported wood pellets for CHP and DH plants (≈40% of bioenergy), domestic agricultural biogas from livestock manure and crop residues (≈25%), and waste incineration/straw (≈35%) [12]. The plan deliberately reduces this to 18 kWh/p/d by phasing out imported pellets while retaining domestic biogas (upgraded to pipeline-quality biomethane), agricultural residues, and waste-to-energy for hard-to-electrify DH and industrial heat.

3.3 The Balance: Does It Close?

Figure 1 answers the central question posed in the introduction. The left pair of bars shows the starting point: demand at 133 kWh/p/d towers over current renewable supply at ≈40, leaving a fossil deficit of ≈93 kWh/p/d. The right pair shows the 2045 endpoint: demand is compressed to ≈101 kWh/p/d and domestic supply reaches ≈103 kWh/p/d through the pillars described above, providing a small margin of ≈2 kWh/p/d. In addition to this domestic balance, the offshore wind surplus of 27.5 kWh/p/d is exported, generating €4–7B/yr in revenue. This diversification is not cosmetic; it is the plan's primary insurance policy against technology-specific risk (see §3.5).

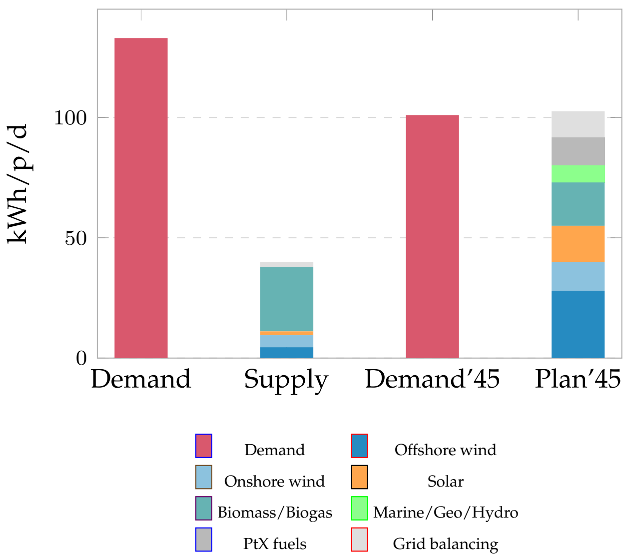

Figure 1: Energy balance: current demand, current renewable supply, 2045 reduced demand, and 2045 plan supply.

3.4 Fiscal Feasibility

Denmark's fiscal position is exceptionally well-suited to financing a 20-year energy transition. Government debt stood at just 27.9% of GDP in 2025, well below the EU average of 83%, the European Commission forecasts a general government surplus of 2.3% of GDP for 2025, and Denmark retains AAA/Aaa credit ratings with stable outlooks from all three major agencies [40, 27, 41]. The IMF (May 2025) specifically concluded that temporary increases in climate spending are manageable within Denmark's fiscal framework [7].

Total investment: €≈96–128 over 20 years (≈1.4% of GDP/year), with ≈65% from private capital (Annex E). Danish pension funds, among the largest per capita in Europe, have already invested or pledged DKK 443B in green-transition assets [42]. The investment is financed through a combination of CfD-backed offshore wind auctions (which attract pension-fund capital at low cost of capital), green sovereign bonds, EU CEF co-financing for the Bornholm Energy Island (€645M [43]), and revenue from the strengthened carbon tax (DKK 750/t CO_2 by 2030 [34]). Denmark could double its debt-to-GDP ratio to 56% and still remain below the EU average.

3.5 Risks and Mitigants

Three main risks threaten execution (see Annex J for full analysis): (i) **offshore wind cost overruns**: the 2024 zero-bid tender proved that fixed-price auctions fail in the current rate environment; the CfD pivot with 20-year price guarantees [46] directly addresses this risk, drawing on the UK experience, where CfD-backed auctions have deployed 14.7 GW of offshore wind [45]; (ii) **grid congestion**: 35 GW of offshore wind feeding into a 6 GW-peak system requires €5–8B in grid investment; the Energy Island concept mitigates this by acting as an offshore hub, routing power to whichever market has the highest price [47]; (iii) **supply chain constraints**: global competition for turbines and cables is acute, but Denmark's domestic supply chain (Vestas #1 globally, Ørsted #1 in offshore development) provides partial insulation. Two further risks, geopolitical vulnerability of North Sea infrastructure and technological uncertainty around PtX costs and wave energy, are analysed in Annex J.

Sensitivity. The plan's robustness rests on diversification. We test four failure modes (detailed in Annex J): (a) offshore at 20 GW instead of 35 collapses exports but domestic balance survives via increased onshore and solar; (b) electrolysers stuck at €800/kW shrinks PtX to 5 GW, offset by biomass retention; (c) wave energy at zero is absorbed by the offshore surplus; (d) Greenland PtX not materialising loses 1.5 kWh/p/d, covered by the domestic margin. The critical single-point dependency is offshore wind permitting. If 35 GW is not reached, the plan recommends pivoting to higher onshore (5% territory, ≈24 kWh/p/d) and solar (1% agri-PV, ≈20 kWh/p/d), at higher land-use cost.

3.6 Geopolitical Dimension

As shown by the plan, Denmark becomes a net exporter of clean energy rather than merely covering domestic demand. Offshore wind creates the export surplus, while hydrogen infrastructure provides an additional export channel. Denmark therefore moves from energy importer to **net exporter and energy technology hub**.

Industrial competitiveness. This export position also has an industrial dimension. A significant share of the investment can be channelled through areas where Denmark already has strong domestic firms: wind turbines and offshore development with Vestas and Ørsted, and heat pumps, power electronics and energy-efficiency solutions with Danfoss. The transition therefore supports not only infrastructure, but also a national clean-tech ecosystem whose expertise can be demonstrated at home and exported abroad. Denmark's energy system becomes a proof case for its industrial capabilities, reinforcing decarbonisation and competitiveness.

Sovereignty and the Arctic. U.S. pressure on Greenland, from the 2019 "real-estate deal" to the January 2026 threat [57], has prompted Denmark's largest peacetime defence build-up: spending above 3% of GDP [50, 4] and a DKK 14.6B Arctic package including a subsea cable [58]. The Greenland hydro-PtX pillar (4b) is a concrete response: it integrates Greenland into the Kingdom's energy system, provides revenue to Nuuk, and makes the territory's development dependent on Danish, not external, infrastructure. The energy transition functions as a sovereignty instrument.

4 Conclusion

The answer to the question posed in the introduction is yes, but conditionally. Denmark can close its full consumption-based energy balance by 2045 by compressing demand from 133 to ≈101 kWh/p/d and scaling renewable supply to match. The demand side works because Denmark already has the infrastructure: a 65%-coverage district-heating network ready for heat-pump electrification, a small territory with short transport distances suited to EVs, and an industrial base dominated by low-temperature processes. The supply side works because Denmark's North Sea bathymetry allows offshore wind deployment at a scale that exceeds domestic needs. This surplus can be converted into export revenue and green hydrogen, while from 2035, Greenland's hydropower adds a Kingdom-wide PtX dimension that strengthens both energy supply and Arctic sovereignty.

The total investment of €≈96–128 over 20 years (≈1.4% of GDP/year) is well within fiscal capacity given Denmark's AAA-rated balance sheet and deep pension-fund capital pool. Demand reduction remains central, but the plan is not hostage to perfect execution: offshore exports can be partly redirected, biomass/biogas provides dispatchable backup, solar and agri-PV offer scalable reserves, and batteries plus interconnectors cover short-term balancing.

At full deployment, offshore wind reaches 55.5 kWh/p/d, with 27.5 kWh/p/d allocated to exports under the baseline scenario, generating €4–7B/yr in combined revenues. Denmark thus moves from the country that *invented* wind power to one that exports clean energy and system know-how. The energy transition functions simultaneously as climate policy, industrial strategy, and geopolitical repositioning. Figure 2 summarises the implementation roadmap, phased over four five-year periods with Go/No-Go gates for each pillar.

5 Use of AI

AI tools (Claude, Anthropic; ChatGPT, OpenAI) were used for: (i) identifying sources when standard search engines did not return relevant results; (ii) extracting and translating information from reports published in Danish; and (iii) editorial refinement of selected passages. All calculations, numerical analysis, assumptions and systemic reasoning remain our own.

The estimated AI energy footprint is approximately 15 kWh. This conservative order-of-magnitude estimate reflects repeated long-context interactions, file analysis and iterative drafting. For a three-person team, it corresponds to roughly 0.09 kWh per author per day.

Implementation Roadmap: Denmark 2045

Figure 2: Implementation roadmap for Denmark 2045, structured across supply, demand and enabling layers over four implementation phases.

	Phase 1: 2025–2030 *Foundations*	**Phase 2: 2030–2035** *Scale-up*	**Phase 3: 2035–2040** *System maturity*	**Phase 4: 2040–2045** *Full deployment & export*
A. SUPPLY: ELECTRICITY GENERATION & FUELS				
Offshore wind €40–52B	Thor 1 GW online (2027). Hesseloe 0.8–1.2 GW tendered. CfD framework operational. *Cumul.* ≈5 GW; 8 kWh/p/d.	Bornholm Energy Island 3.5 GW online (2032). North Sea package 2.8 GW. *Cumul.* ≈11 GW; 17 kWh/p/d.	North Sea Energy Island 3 GW. Further tenders 10 GW. Export revenues begin: €2–3B/yr. *Cumul.* ≈24 GW; 38 kWh/p/d.	Final tenders 8–11 GW. Fleet reaches 32–35 GW; 51–55 kWh/p/d. Export revenues: €4–7B/yr.
Solar PV €10–15B	Rooftop PV expands from 4 to 10 $\mathrm{GW_p}$. NECP target: 20 $\mathrm{GW_p}$ by 2030. Agri-PV pilots.	20 $\mathrm{GW_p}$ target met. First agri-PV farms on 0.2% of territory. Output: ≈10 kWh/p/d.	Agri-PV expands to 0.5% of territory. Rooftop potential largely saturated. Output: ≈13 kWh/p/d.	Maintenance and repowering. Full output reaches ≈15 kWh/p/d.
Onshore wind €6–7B	Repowering begins. Capacity rises from 4.8 to 6 GW by replacing older 1–2 MW turbines with 5–7 MW units.	Repowering continues. Effective capacity reaches ≈8 GW. Output: ≈8 kWh/p/d.	Territorial coverage reaches 2.5%. Output reaches ≈12 kWh/p/d.	Maintenance mode. Community ownership exceeds 50%, supporting long-term local acceptance.
PtX mainland €10–15B	4 GW of electrolysers installed. Esbjerg–Germany hydrogen pipeline online by 2030. EU co-funding secured.	Capacity expands to 7 GW. Hydrogen exports via pipeline begin. Sustainable aviation fuel pilot launched.	Capacity expands to 10 GW. Green H_2 reaches €2–3/kg. SAF blending mandates enacted.	Full capacity reached. PtX provides 10 kWh/p/d net output, requiring ≈14 kWh/p/d gross input at 70% efficiency.
Greenland PtX ≈€3B	Feasibility studies completed. Buksefjord hydro expansion begins. Danish–Greenlandic business framework established.	Buksefjord expansion online by 2032. Electrolyser pilot at Nuuk. Ammonia tanker route to Esbjerg designed.	First tanker deliveries to Esbjerg. Output reaches ≈0.5 kWh/p/d. Second hydro site under development.	Scale-up to 1.5 kWh/p/d. Hydro input reaches 5,000 GWh/yr. Strategic Denmark–Greenland energy link operational.
Biomass/biogas ≈€2B	Imported-pellet phase-down begins. Biogas upgraded to biomethane.	Pellet imports halved. Domestic biogas exceeds 30% of bioenergy supply.	Biomass use declines from 26.7 to 20 kWh/p/d. Straw and residue use optimised.	Target reaches 18 kWh/p/d. Biomass supply becomes domestic-only, with no imports.
B. DEMAND: BUILDINGS, TRANSPORT, INDUSTRY				
Heat revolution €8–12B	District-heating electrification rises from 2.6 to 6 GW. Heat pump rollout begins for 400,000 gas-heated homes.	6 GW district-heating target met. 200,000 homes converted. Renovation rate reaches 3%/yr. HVAC demand falls to 22 kWh/p/d.	350,000 homes converted. Pre-1980 housing stock largely renovated. HVAC demand falls to ≈20 kWh/p/d.	Full conversion achieved. HVAC demand falls to ≈18.5 kWh/p/d. Gas heating phase-out complete.
Transport	EV share rises from 30% to 60%. EU ban on new combustion-engine cars takes effect in 2035. Fehmarn Belt tunnel construction advances.	EV share rises from 60% to 80%. Fehmarn Belt opens around 2029. Copenhagen–Hamburg becomes a 2.5-hour electrified rail corridor.	EV share rises from 80% to 95%. Charging infrastructure matures. Short-haul aviation declines.	EV fleet reaches 100%. Car demand falls from 11.3 to 6.2 kWh/p/d. Aviation demand falls from 8.0 to 6.0 kWh/p/d.
C. ENABLING: GRIDS, STORAGE, REGULATION				
Grid & interco. €6–10B	Energinet begins grid reinforcement programme. Bornholm interconnector becomes operational. Congestion-relief investments launched.	Interconnector capacity reaches ≈11 GW. Energy Island hub routes power to highest-price markets. Bidirectional cross-border flows optimised.	HVDC backbone upgraded. New interconnector to Poland assessed. Smart-grid technologies rolled out.	Full grid integration achieved. Balancing capacity reaches 11 kWh/p/d. Real-time electricity market coupling across connected markets.
Batteries & flex €2–3B	First utility-scale lithium-ion batteries deployed with 4-hour duration. Frequency-regulation contracts awarded.	2–3 GW of battery storage deployed, co-located with solar farms for output smoothing.	Grid-forming inverters deployed to maintain frequency stability. Vehicle-to-grid integration expands with the EV fleet.	Full flexibility stack operational. Intra-day balancing mature across all market zones.
Regulatory	Contracts for Difference framework enacted. Carbon tax ramps to DKK 750/tCO_2 by 2030. NECP submitted to the EU. Green sovereign bond programme launched.	Carbon tax reaches full rate. Mandatory building energy performance standards introduced. Hydrogen certification framework established.	EU ETS extended to buildings and road transport. Circular-economy legislation enacted. Industrial emissions caps tightened.	Net-zero target formally verified. Climate Act 2045 compliance audit conducted by the independent Climate Council. Post-2045 export strategy adopted.
Cumul. capex	≈€20–25B	≈€45–55B	≈€70–85B	≈€96–128B *(total)*
Supply	≈50 kWh/p/d	≈70 kWh/p/d	≈90 kWh/p/d	≈103 kWh/p/d
Demand	≈125 kWh/p/d	≈115 kWh/p/d	≈108 kWh/p/d	≈101 kWh/p/d
Fossil gap	≈75 kWh/p/d	≈45 kWh/p/d	≈18 kWh/p/d	0 Net-zero achieved

Note. Cumulative figures are approximate midpoints. PtX kWh/p/d figures are *net output* after ≈70% electrolysis efficiency. The Phase 3→4 offshore ramp has been smoothed from 24 to 32–35 GW to avoid an unrealistic deployment step. Phase transitions remain conditional on technical delivery, grid readiness, social acceptance, cost control and regulatory approval. See Annex L for glossary of abbreviations.

Annexes

A Technology costs Assumptions

Table 3: Technology cost assumptions

Technology	Installed cost	LCOE	Our model	Source
Offshore wind	USD 2,852/kW	USD 0.079/kWh	€40–52B total	IRENA [13]; pipeline [5, 10, 36]
Onshore wind	USD 1,041/kW	USD 0.034/kWh	€6–7B	IRENA [13]
Solar PV (utility)	USD 691/kW	USD 0.043/kWh	€10–15B	IRENA [13]
Electrolyser (PEM/ALK)	USD 750–1,300/kW*	—	€8–12B	IEA GHR [14]
Heat pump (large DH)	€0.8–1.2M/MW_{th}	—	incl. Pillar 3	DEA [15]
Battery storage (4h)	USD 192–350/kWh	—	incl. Grid	IRENA [13]
Wave energy	USD 3,000–6,000/kW	USD 0.15–0.30/kWh	€4–5B	IEA-OES [16]
Geothermal (deep)	€5–10M/MW_{th}	—	€2–3B	DEA [15]
Grid interconnection	€0.9–1.5B/GW	—	€8–13B total	Viking Link; COBRA; TenneT [17, 18, 19]
Building renovation	€150–300/m^2	—	incl. Pillar 3	Housing Europe; EU [20, 23]

Note: USD/EUR at 0.92. IRENA values are global weighted-average benchmarks. The "Our model" column gives the planning budget used in this report; it should not be read as a direct project quote or as a mechanical conversion of each benchmark cost. *Electrolyser costs correspond to low-cost/scaled deployment benchmarks rather than current European average installed costs.

B Denmark's Fiscal Scorecard

Table 4: Fiscal and macroeconomic indicators

Indicator	Value	Year	Source
Nominal GDP	DKK 2,935B (≈€394B)	2025	Statistics Denmark [24]
Real GDP growth	2.4% / 2.0%	2025e / 2026e	OECD [26] / EC [27]
Government debt / GDP	27.9%	Dec 2025	Statistics Denmark [24]
Budget surplus / GDP	2.3%	2025e	EC [27]
Sovereign credit rating	AAA (stable)	2025	S&P [28]
10-year sovereign yield	≈2.8%	May 2026	Banque de France [35]
Currency reserve	DKK 650B (≈22% GDP)	2025	Danmarks Nationalbank [29]
Pension fund climate commits	DKK 443B	2024	ICLG [9]
Carbon tax (industry)	DKK 750/t CO_2 by 2030	enacted 2024	Min. of Finance [34]

Note: The IMF (May 2025) concluded that Denmark's fiscal position is robust and temporary increases in climate spending are manageable [7].

C Offshore Wind Projects Pipeline

Table 5: Offshore wind projects

Project	Capacity	Online	Est. cost / support	Ref.
Existing fleet	2.5–2.7 GW	oper.	—	[2, 5]
Thor (RWE)	1.0 GW	2027	n.a.	[36]
Hesselsø	0.8–1.2 GW	2032	support cap: DKK 27.4B	[5, 36]
Bornholm Energy Island	3.0–3.8 GW	2032	€7B	[10, 36]
North Sea tender package	2.8 GW	2032–34	support cap included in DKK 55.2B	[5]
North Sea Energy Island	3.0 GW	2035–40	€8B hub; broader system higher	[4, 36]
Further tenders	15–20 GW	2035–45	planning assumption	[5, 4]
Total by 2045	**≈30–35 GW**		**€40–52B***	

Note: Reported public support caps are not CAPEX estimates. The total cost range is a planning assumption combining named projects, energy-island infrastructure, and future tender rounds.

D Demand Reduction: Detailed Justification

Table 6: Demand reduction levers (−24%, from 133 to 101 kWh/p/d)

Lever	Saving	From → To	Mechanism	Source
Heat pumps in DH	−6	28.5 → 22.5	COP 3–4 replaces gas boilers; 65% DH coverage; electrified heat capacity already scaling rapidly	DBDH/State of Green [33]
Building renovation	−4	22.5 → 18.5	Deep renovation of inefficient pre-1980 buildings; aligned with EU Renovation Wave policy direction	EU [23]
Full EV fleet	−5	11.3 → 6.3	Electric motor η 85–90% vs. ICE 25–30%; EU phase-out of new combustion cars by 2035	DEA; EU [2, 32]
Fehmarn Belt rail	−2	8.0 → 6.0	Modal shift from short-haul aviation to electrified rail; Fehmarn Belt link reduces Copenhagen–Hamburg travel time	Femern/BMDV [31]
Industry electrif.	−5	68 → 63	Electrification of low-temperature heat, efficiency gains, circularity and lower material intensity	DEA [2]
Appliances/LED	−3	4.9 → 1.9	Continued efficiency gains from EU Ecodesign and LED penetration	DEA; EU [2, 8]
Other/Public	−7	—	System efficiency, avoided conversion losses from electrification, reduced fossil primary-energy losses	MacKay; IDA [1, 6]
Total	**−32**	**133 → 101**		

Table 7: Denmark's energy resource endowments

Resource	Quality	Scale	Strategic implication	Source
North Sea wind	A+	A+	Shallow waters, strong offshore wind resource, Vestas/Ørsted industrial base	IEA; ScottMadden [3, 4]
Onshore wind	A	B	Good resource, but land-constrained on a small territory	DEA [2]
Solar PV	B	A	Moderate irradiance, but large rooftop potential and selectively usable agricultural land through agri-PV; farmland acts as scalability reserve	PVGIS; World Bank [37, 22]
District heating	A+	A+	High coverage; strong platform for large-scale heat-pump integration	IEA; DBDH [3, 33]
Biomass/Biogas	A	A	Significant current role; useful for residual heat, biogas and hard-to-electrify uses	IEA Bio [12]
Wave & Tidal	B	B	Long coastline and theoretical potential, but technology remains less mature	MacKay [1]
Hydropower	D	D	Very low elevation; negligible contribution potential	DEA [2]
Geothermal	B-	B	Low-to-moderate resource; useful mainly as district-heating baseload	DEA [15]
Interconnectors	A+	A	Strong cross-border position; key for balancing and exports	Energinet [21]

Note: Grades are the authors' qualitative assessment based on resource quality, scalability, maturity, and strategic fit with Denmark's energy system. Sources support the underlying factual indicators, not the grades themselves.

E Investment Budget Breakdown

Table 8: Cumulative investment 2025–2045

Pillar	Public (€B)	Private (€B)	Total (€B)	Instrument
1. Offshore wind	8–12	32–40	40–52	CfD; pension funds
2. Solar PV	2–3	8–12	10–15	PPAs; agri-PV grants
3. Heat revolution	3–4	5–8	8–12	Subsidies; DH tariffs
4. Power-to-X	3–5	7–10	10–15	H_2 contracts; IPCEI
5a. Grid & interco.	4–6	2–4	6–10	Energinet; green bonds
5b. Battery storage	1–2	1–2	2–3	Li-ion 4h; frequency reg.
Total	**21–32**	**55–76**	**76–107**	

Mid-point: €90B / 20 yrs = €4.5B/yr = **1.14% of GDP**
Debt headroom: DK could double debt/GDP to 56% and remain below EU avg (83%)

Table 9: Cost-effectiveness analysis by technology

Technology	Plan output (kWh/p/d)	Capex mid (€B)	Cost per (kWh/p/d) (€B)	LCOE (€ct/kWh)	Comment
Offshore wind (dom.)	28.0	46	1.6	7.9	Lowest LCOE; backbone of plan. Export revenue (27.5 kWh/p/d additional) improves effective cost further. **Scalable**: EEZ could support 50+ GW.
Onshore wind	12.0	6.5	0.5	3.4	**Most cost-effective source.** Repowering leverages existing sites. **Limited**: territory small, 5% coverage is practical ceiling.
Solar PV	15.0	12.5	0.8	4.3	Good cost-efficiency; seasonal complementarity with wind adds system value beyond LCOE. **Scalable**: farmland reserve allows up to 3% territory.
Biomass / Biogas	18.0	≈2	0.1	n/a	Phase-down from 26.7; low incremental cost (retain existing assets). Highest €/kWh efficiency of any pillar. **Not scalable**: depends on domestic residues; expanding requires imports.
Wave & Tidal	5.0	≈5	1.0	15–30	Pre-commercial; highest LCOE. Included for diversification, not cost-efficiency. **Moderately scalable**: long coastline, but technology maturity is the constraint.
Geothermal	2.0	≈2.5	1.3	n/a (heat)	DH baseload heat, not electricity. Moderate cost but high utilisation (CF >85%). **Limited**: low-temperature resource, ceiling ≈3–4 kWh/p/d.
PtX (mainland)	10.0	12.5	1.3	n/a (fuel)	Molecular fuels; cost driven by electrolyser price trajectory. Breakeven at €300/kW. **Scalable**: limited only by electricity surplus.
Greenland hydro-PtX	1.5	≈3	2.0	n/a (fuel)	Highest per-unit cost, but strategic value (sovereignty, dispatchable H_2). Included from 2035. **Highly scalable**: 20,000 GWh/yr potential, plan uses <25%.
Grid & interco.	11.0	8	0.7	n/a (flex.)	Flexibility, not generation. Enables bidirectional balancing flows; no LCOE applicable. **Scalable**: new links (e.g. DK–PL) possible.
Battery storage	—	2.5	n/a	n/a (flex.)	No energy output; provides intra-day flexibility. Cost benchmarked at €192–350/kWh (4h Li-ion). **Scalable**: modular, costs declining rapidly.
Heat revolution	−10 (demand)	10	1.0	n/a (saved)	Demand reduction, not supply. Each kWh/p/d saved avoids building supply capacity. **Limited**: once stock is renovated, savings plateau.
Total plan	**102.6 supply**	**≈€90B**	**0.9 avg**		Demand reduced from 133 to ≈101; supply from ≈40 to ≈103. Net gap closed: ≈63 kWh/p/d. Effective cost: **€1.4B per kWh/p/d of gap closed**.

Methodology: "Cost per kWh/p/d" = capex midpoint / plan output. LCOE values from IRENA 2024 global weighted averages [13], converted at USD/EUR 0.92. The effective plan cost of €1.4B per kWh/p/d of gap closed (≈€90B / 63 kWh/p/d) benchmarks well against comparable European transition plans. **Ranking by cost-efficiency**: (1) biomass retention (€0.1B/unit), (2) onshore wind (€0.5B), (3) grid (€0.7B), (4) solar (€0.8B), (5) heat demand reduction (€1.0B), (6) wave (€1.0B), (7) PtX (€1.3B), (8) geothermal (€1.3B), (9) offshore wind (€1.6B), (10) Greenland PtX (€2.0B). Note that offshore wind's effective cost improves significantly when export revenues (€4–7B/yr) are included; its net cost after 20 years of exports is negative.

F Load Factor and Utilisation Assumptions

Load factors convert installed capacity (GW) into energy output (kWh/p/d). In this report, they are used directly only for GW-based technologies, namely offshore wind and Power-to-X. Onshore wind and solar PV are derived separately using the MacKay-style territorial approach detailed in Annex K.

$$\text{LF} = \frac{\text{Annual production [MWh]}}{\text{Installed capacity [MW]} \times 8760 \text{ h/yr}}$$

Table 10: Load-factor and utilisation assumptions for GW-based technologies

Technology	Installed	Production	Factor used	Source
Offshore wind	2.5 GW	8.7 TWh	39.7%	DEA [2]
PtX electrolysers	10 GW	target-based	29.7%†	Model assumption

Example: Offshore wind: $\frac{8.7\times10^6}{2{,}500\times8{,}760} = 0.397 \approx 39.7\%$. Then 35 GW at 39.7% yields $\frac{35\times10^6\times0.397\times8760}{5{,}993{,}000\times365} \approx 55.6$ kWh/p/d.

†*PtX note*: The 29.7% value is not an empirical load factor. It is an effective output factor used to size the Power-to-X pillar from the plan's energy need. The model assumes that 10 GW of electrolysers deliver approximately 10 kWh/p/d of net usable PtX output. Before downstream losses, this corresponds to about 26 TWh/yr of hydrogen output, or ≈11.9 kWh/p/d gross. This is obtained by assuming 65% electrolyser efficiency and around 4,000 equivalent full-load hours per year: $65\% \times 4{,}000/8{,}760 = 29.7\%$. After storage, compression and transport losses, the gross output is rounded down to 10 kWh/p/d net usable PtX output.

G Regulatory & Governance Timeline

Table 11: Key milestones

Year	Instrument	Significance	Source
1979	Heat Supply Act	Mandatory municipal heat planning; established DH framework	IEA [3]
1985	Nuclear moratorium	Parliament bans nuclear power; Denmark commits to renewables-only	IEA [3]
1991	Vindeby	World's first offshore wind farm (11 turbines, 5 MW)	DEA [2]
1999	Electricity Reform	Liberalisation of the electricity market; creation of Energinet	DEA [2]
2008	RE Promotion Act	20% local ownership requirement for new wind projects	IEA [53]
2012	Energy Agreement	Target: 50% wind in electricity by 2020 (achieved 2019)	IEA [3]
2019	Climate Act	−70% by 2030; net-zero by 2050; independent Climate Council	ScottMadden [4]
2020	Esbjerg H_2 Declaration	Joint DK/DE/NL/BE commitment to North Sea green H_2 hub	[10]
2022	Green Tax Reform	DKK 750/t CO_2 by 2030 (among highest globally)	Min. Fin. [34]
2024	Tender failure	6 GW offshore zero bids; exposes fixed-price model failure	CoralPoint [5]
2024	Solar milestone	Installed PV surpasses 4 GW_p; 11.2% of electricity	[54]
2025	CfD re-tender	2.8 GW with 20-yr price guarantees; policy pivot	CoralPoint [5]
2025	2045 net-zero	Target advanced from 2050 to 2045	ScottMadden [4]
2025	Bornholm start	Energy Island construction begins; EU CEF €645M	State of Green [10]
2025	Arctic package	DKK 14.6B defence; subsea cable to Greenland	[58]
2026	Defence >3% GDP	Largest peacetime military spending; North Sea protection	[50]

H Hydrogen in Aviation: Readiness Assessment

Airbus's ZEROe programme, originally targeting commercial hydrogen aircraft by 2035, has been delayed to the 2040s due to insufficient hydrogen infrastructure development [38]. The European Destination 2050 roadmap (2nd edition) reduced hydrogen aviation's expected contribution to decarbonisation from 20% to just 6% [39].

Implication for our plan: Power-to-X capacity (10 GW) is primarily allocated to **green hydrogen for shipping, heavy trucking, and industrial feedstock**, sectors where hydrogen is closer to commercial viability. Aviation decarbonisation in the plan relies on **Sustainable Aviation Fuel (SAF)**, which can be blended into existing jet fuel and aircraft. Denmark's PtX infrastructure can produce synthetic kerosene (power-to-liquid) as a SAF pathway, providing optionality: if hydrogen aviation matures by the 2040s, the electrolyser capacity is already in place.

I Grid Integration: Interconnector Portfolio

Denmark's interconnector portfolio provides a flexibility layer rather than a primary energy source. It enables imports during low-wind or high-demand hours and exports during renewable-surplus periods, while supporting Denmark's role as a net annual exporter of green energy.

Table 12: Cross-border interconnectors and offshore hubs

Link	Current	Planned	Online	Source
DK–Norway, Skagerrak 1–4	1,700 MW	—	oper.	Energinet [21]
DK–Sweden, Konti-Skan / Øresund	2,440 MW	—	oper.	Energinet [21]
DK–Germany, Kontek / Kriegers Flak / Jutland links	2,500 MW	+400 MW	2028	Energinet [21]
DK–Netherlands, COBRAcable	700 MW	—	oper.	Energinet [21]
DK–UK, Viking Link	1,400 MW	—	2023	Energinet [21]
Bornholm Energy Island hub	—	2,000 MW	2032	State of Green [10]
Total	**≈8.7 GW**	**≈2.4 GW**		**≈11.1 GW by 2032**

Note: The 11 kWh/p/d import figure used in the plan corresponds to a modelled balancing flow of roughly 24 TWh/yr, not to permanent import dependence. At 11.1 GW of interconnector capacity, this would imply an average net-import utilisation of about 25%. In practice, flows are bidirectional: Denmark imports during low-wind or high-demand periods and exports during renewable-surplus periods. Electricity exports, PtX production and hydrogen exports are therefore treated as outputs of domestic renewable surplus, while imports are treated as system-balancing flows.

J Risk Analysis (Expanded)

1. Offshore wind procurement risk. The December 2024 tender failure (zero bids for 6 GW) demonstrated that fixed-price, no-subsidy auctions do not work in the current interest rate environment [5]. The government's November 2025 pivot to CfD contracts with 20-year price guarantees directly addresses this. CfDs cap both developer downside (floor price) and public upside (ceiling price), as proven in the UK (which has used CfDs since 2014 to deploy 14.7 GW offshore). *Residual risk*: if NordPool wholesale prices collapse, CfD payments increase public cost. Mitigant: Denmark's diversified export markets (4 countries) reduce single-market dependence.

2. Grid congestion and curtailment. With 35 GW offshore feeding into a system historically sized for ≈6 GW peak demand, massive reinforcement is needed. Energinet's System Plan 2024 [21] allocates €5–8B for grid expansion. The Energy Island concept mitigates this by acting as an offshore hub: power flows to whichever market (DK/DE/SE/NO) has the highest price, reducing domestic grid stress. *Residual risk*: permitting delays for onshore grid upgrades. Mitigant: 2023 Energy Parks framework streamlines permitting.

3. Supply chain bottlenecks. Global offshore wind deployment (to ≈380 GW by 2030) creates competition for turbines, foundations, and installation vessels. Denmark is partially insulated: Vestas (HQ: Aarhus) and Ørsted (HQ: Fredericia) are the global #1 turbine manufacturer and #1 offshore developer respectively. However, subsea cable manufacturing (NKT, Prysmian) and transformer supply remain European-wide bottlenecks. *Mitigant*: EU Wind Power Package (2023) and European Wind Charter aim to coordinate supply chains [3].

4. Geopolitical / North Sea infrastructure risk. Subsea cables and pipelines are vulnerable to sabotage (cf. Nord Stream, 2022). Denmark has responded by increasing defence spending to 3.25% of GDP (2026) and participating in NATO's Critical Undersea Infrastructure initiative [4]. The Energy Island itself provides physical redundancy: multiple cable routes to multiple countries.

5. Technology risk (PtX and wave). Electrolyser costs must fall from ≈€800/kW to ≈€300/kW for green H_2 to compete with grey H_2. The IEA projects this by 2030 at scale [14]. Wave energy remains pre-commercial; our plan allocates only 5 kWh/p/d (6% of supply), limiting exposure. If wave underdelivers, additional offshore wind (already in excess) compensates.

K Detailed Deployment Plan

This annex presents the full calculation chain for each pillar of the 2045 plan. **Offshore wind** is computed from installed capacity and an empirical load factor derived from DEA data (Annex F). **Power-to-X** is treated as a target-based utilisation assumption sized from the plan's net usable PtX output requirement. **Onshore wind** and **solar PV** follow the Excel workbook's MacKay-style territorial approach: power density (W/m^2) × territory coverage × efficiency. Cost assumptions are reported in Annex A, while named offshore projects and tender assumptions are detailed in Annex C.

Pillar 1: Offshore Wind — 35 GW

Table 13: Offshore wind deployment: phase-by-phase

Phase	Added (GW)	Cumul. (GW)	Output (kWh/p/d)	Capex (€B)	Period
Existing fleet	—	2.5	4.0	—	operational
Thor + Hesselsø	2.0	4.5	7.1	3–4	2027–32
Bornholm Energy Island	3.5	8.0	12.7	7	2032
North Sea tender package	2.8	10.8	17.2	4–5	2032–34
North Sea Energy Island	3.0	13.8	21.9	5–8	2035–40
Tenders 2035–40	10.0	23.8	37.8	13–15	2035–40
Tenders 2040–45	11.2	35.0	55.6	14–15	2040–45
Total	**32.5**	**35.0**	**55.5**	**≈40–52**	

Calculation: $E = \frac{P \times 0.397 \times 8760 \times 10^6}{5{,}993{,}000 \times 365}$. At 35 GW, this yields ≈55.6 kWh/p/d, rounded to 55.5 kWh/p/d in the main text. Domestic allocation: 28.0 kWh/p/d. Export surplus: ≈27.5 kWh/p/d, equivalent to roughly 48 TWh/yr. The cost range is a planning assumption combining named projects, energy-island infrastructure and future tender rounds; public support caps are not treated as CAPEX.

Onshore Wind — 12 kWh/p/d

Table 14: Onshore wind deployment using the territorial methodology (based on Excel file)

Parameter	Value
Average wind speed	6.47 m/s
Air density	1.3 kg/m^3
Turbine diameter	25 m
Wind turbine efficiency	50%
Power density over land area	2.77 W/m^2
Danish territory	42,925 km^2
Coverage	**Output (kWh/p/d)**
2.5% of territory, plan assumption	**$\approx$ 12**

The 2.5% coverage assumption is interpreted as a combination of repowering and selective additional deployment. Modern 5–7 MW turbines can replace older 1–2 MW units on already accepted sites, increasing output per site without proportional new land take. The resulting investment is treated as a planning allowance of €6–7B, consistent with an equivalent additional capacity of roughly 6–7 GW at about €1.0B/GW.

Pillar 2: Solar PV — 15 kWh/p/d

Table 15: Solar PV deployment using the territorial methodology

Segment	Parameter	Output (kWh/p/d)	Capex (€B)
Rooftop PV	10 m^2/p $\times$ 20% η $\times$ 114 W/m^2	5.5	3–4
Solar farms / agri-PV	0.5% territory $\times$ 10% η $\times$ 114 W/m^2	9.8	7–11
Total		**15.3 $\approx$ 15**	**10–15**

Excel sheet `Solar`: average irradiance 114 W/m^2 from the PVGIS DATA Solar sheet. Rooftop PV assumes 10 m^2 per person at 20% panel efficiency. Utility-scale agri-PV uses 0.5% of Denmark's territory, i.e. about 215 km^2, at 10% system efficiency, including spacing and system losses. This deliberately uses agricultural land selectively rather than maximising it: Denmark's farmland base is treated as a scalability reserve if offshore wind deployment, PtX costs or grid constraints underperform.

Pillar 3: Heat Revolution

Table 16: Heat electrification pathway

Measure	Saving (kWh/p/d)	Capex (€B)	Timeline
Large DH heat pumps and electric boilers	−4.5	5–6	2025–35
Current: nearly 2.6 GW electricity-based heat capacity			[33]
Individual heat pumps for gas-heated homes	−2.5	2–3	2025–35
Deep building renovation	−3.0	3–4	2025–45
Total HVAC reduction	**−10**	**10–13**	

Heat pumps reduce delivered-heat primary energy because each kWh_{th} requires only about 0.25–0.33 kWh_{elec} at COP 3–4, compared with gas boilers close to COP $\approx$0.9. Together with renovation, this drives the HVAC reduction from 28.5 to approximately 18.5 kWh/p/d, as detailed in Annex D.

Pillar 4: Power-to-X — 10 GW Electrolysers

Table 17: Power-to-X deployment

Phase	Capacity (GW)	Net output (kWh/p/d)	Capex (€B)	End use
2025–30, early deployment	4	4.0	3–4	Industry, shipping
2030–35, scale-up	+3	7.0	3–5	Export via Esbjerg–Germany pipeline
2035–45, mature phase	+3	10.0	4–6	SAF / power-to-liquid optionality
Total	**10 GW**	**10.0**	**10–15**	

The PtX pillar is sized from the plan's energy need rather than from an externally reported load factor. The model assumes that 10 GW of electrolysers deliver approximately 10 kWh/p/d of net usable PtX output. Before downstream losses, this corresponds to about 26 TWh/yr of hydrogen output, or ≈11.9 kWh/p/d gross. This is obtained by assuming 65% electrolyser efficiency and around 4,000 equivalent full-load hours per year: $65\% \times 4{,}000/8{,}760 = 29.7\%$. After storage, compression and transport losses, the gross output is rounded down to 10 kWh/p/d net usable PtX output. The €10–15B range covers electrolysers plus balance-of-plant, storage, compression and export-readiness costs.

Pillar 5: Grid Integration and Balancing Imports — 11 kWh/p/d

Grid integration is not treated as domestic renewable generation. It is a flexibility layer that allows Denmark to import electricity during low-wind or high-demand periods and export during renewable-surplus periods. The 11 kWh/p/d figure corresponds to a modelled annual balancing flow, not to permanent import dependence.

Table 18: Grid integration and balancing role

Component	Capacity / flow	Capex (€B)	Role
Existing and planned interconnectors	≈11.1 GW by 2032	included	Cross-border balancing and export routes
Modelled balancing imports	11 kWh/p/d, ≈24 TWh/yr	—	Low-wind / high-demand adequacy support
Grid reinforcement and storage	system-level investment	8–13	Congestion relief, stability and bidirectional flows
Total grid and storage allowance		**8–13**	

At 11.1 GW of interconnector capacity, a 24 TWh/yr net-import balancing flow would imply about 25% average net-import utilisation. In practice, flows are bidirectional. Denmark imports when system conditions require it and exports when domestic renewable generation exceeds domestic demand. Electricity exports, PtX output and hydrogen exports are therefore treated as outputs of domestic renewable surplus, while imports are treated as system-balancing flows. See Annex I for the interconnector portfolio.

Other Renewable Contributions — Biomass, Biogas, Wave, Tidal, Geothermal and Hydro

Beyond the five main pillars, the plan retains a set of complementary renewable resources. Biomass and biogas play the largest role in this group, but they are treated differently from wind, solar, wave or tidal power. They are not expanded aggressively: instead, the plan deliberately reduces their contribution from today's level, while preserving domestic biogas, agricultural residues and residual hard-to-electrify uses. Wave, tidal, geothermal and hydro are derived from the Excel workbook and treated as smaller diversification resources.

Table 19: Complementary renewable resources

Source	Excel / current basis (kWh/p/d)	Plan allocation (kWh/p/d)	Rationale
Biomass / biogas	26.7 current	18.0	Phase-down of imported biomass; retain domestic biogas, agricultural residues and residual hard-to-electrify uses.
Wave energy	9.15 Excel potential	3.0	Conservative use of coastline potential; technology risk remains high.
Tidal stream farms	0.64 Excel potential	—	Limited Danish tidal-stream resource; treated as secondary option.
Tidal barrages	3.89 Excel potential	1.0	Partial retained contribution; higher output potential but stronger environmental and permitting constraints.
Tidal lagoons	2.70 Excel potential	1.0	More modular option; retained as a complementary tidal contribution.
Geothermal	0.11 current / low electric potential	2.0	Treated as district-heating baseload heat, not as major electricity generation.
Hydro	0.37 Excel theoretical potential	0.1	Very limited elevation; only micro-hydro contribution retained.
Total retained		**25.1**	Biomass/biogas plus smaller complementary renewable resources.

Note: Biomass/biogas is not derived from the Excel workbook's renewable-potential sheets. It is retained as a strategic residual resource based on current Danish bioenergy use and then reduced from 26.7 to 18.0 kWh/p/d to avoid excessive reliance on imported biomass. Wave, tidal, geothermal and hydro are based on the Excel workbook. The plan retains only 5.0 kWh/p/d from wave and tidal resources combined, split as 3.0 from wave energy and 2.0 from tidal options, to reflect technology maturity, site-specific constraints and permitting risk. Geothermal is interpreted as district-heating baseload heat rather than major electricity generation.

Biomass and biogas are therefore not a growth pillar in the plan. They act as a controlled residual backbone: domestic biogas, agricultural residues and sustainable biomass are retained for district heating, industrial heat and hard-to-electrify uses, while imported wood pellets and large-scale combustion are progressively reduced. This is why the plan allocates 18.0 kWh/p/d to biomass/biogas, below the current estimate of 26.7 kWh/p/d.

Wave energy is the largest complementary resource in the workbook. The calculation gives 9.15 kWh/p/d, but the plan retains only 5.0 kWh/p/d to reflect technology maturity and deployment risk. Tidal power is more constrained: the workbook evaluates tidal-stream farms, barrages and lagoons at 0.64, 3.89 and 2.70 kWh/p/d respectively, but the plan does not add these options mechanically. It retains a lagoon-style contribution of roughly 2–3 kWh/p/d because barrages are more exposed to environmental and permitting constraints.

Geothermal is treated separately. The workbook's current production estimate is only about 0.11 kWh/p/d, and electricity-generation potential remains limited. In the plan, the 2.0 kWh/p/d allocation therefore refers to geothermal heat used as district-heating baseload, not to geothermal electricity.

Summary: Plan 2045 at a Glance

Table 20: Complete plan summary

Pillar / source	Target	Domestic (kWh/p/d)	Export (kWh/p/d)	Capex (€B)
1. Offshore wind	35 GW	28.0	27.5	40–52
2. Solar PV	rooftop + 0.5% agri-PV	15.0	—	10–15
3. Heat revolution	6,000 MW DH + renovation	demand −10	—	10–13
4a. Power-to-X (mainland)	10 GW electrolysers	10.0	partial	10–15
4b. Greenland hydro-PtX	hydro $\rightarrow H_2$ tanker	1.5	—	≈3
5a. Grid + interco.	11 GW interco.	11.0	—	6–10
5b. Battery storage	Li-ion 4h	flex.	—	2–3
Onshore wind	2.5% territory	12.0	—	6–7
Biomass / biogas	phasedown	18.0	—	≈2
Wave / tidal / geo / hydro	various	7.1	—	6–8
Total supply		**≈103**	**27.5+**	**≈96–128**
Target demand		**≈101**		
Balance		+2		

The capex range combines the core investment budget with additional renewable-resource deployment. It is therefore broader than the five-pillar budget table because it includes onshore wind, biomass/biogas and smaller complementary sources explicitly.

L Glossary of Abbreviations

CfD	Contract for Difference
COP	Coefficient of Performance
DEA	Danish Energy Agency
DH	District Heating
DKK	Danish Krone
EU ETS	EU Emissions Trading System
GHG	Greenhouse Gas
GW	Gigawatt (10^9 W)
IDA	Danish Society of Engineers
IPCEI	Important Project of Common European Interest
kWh/p/d	kWh per person per day
LF	Load Factor
LCOE	Levelised Cost of Energy
PtX	Power-to-X
RE	Renewable Energy
SAF	Sustainable Aviation Fuel
TES	Total Energy Supply

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