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# Innovations in Pumped Storage

## Thomas Lowe Gray Lecture

Institution of Mechanical Engineers
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*"The times they are a-changing"*

*"Decarbonisation has produced high levels  of renewable generation which has different operating characteristics, plant dynamics, data quality, flexibility and inertia contribution. This  has increased reserve and response requirements and the nature of intermittent renewable generation means that the requirements are more volatile and less predictable."*

Quote from Introduction of National Grid's Operability Strategy 2018

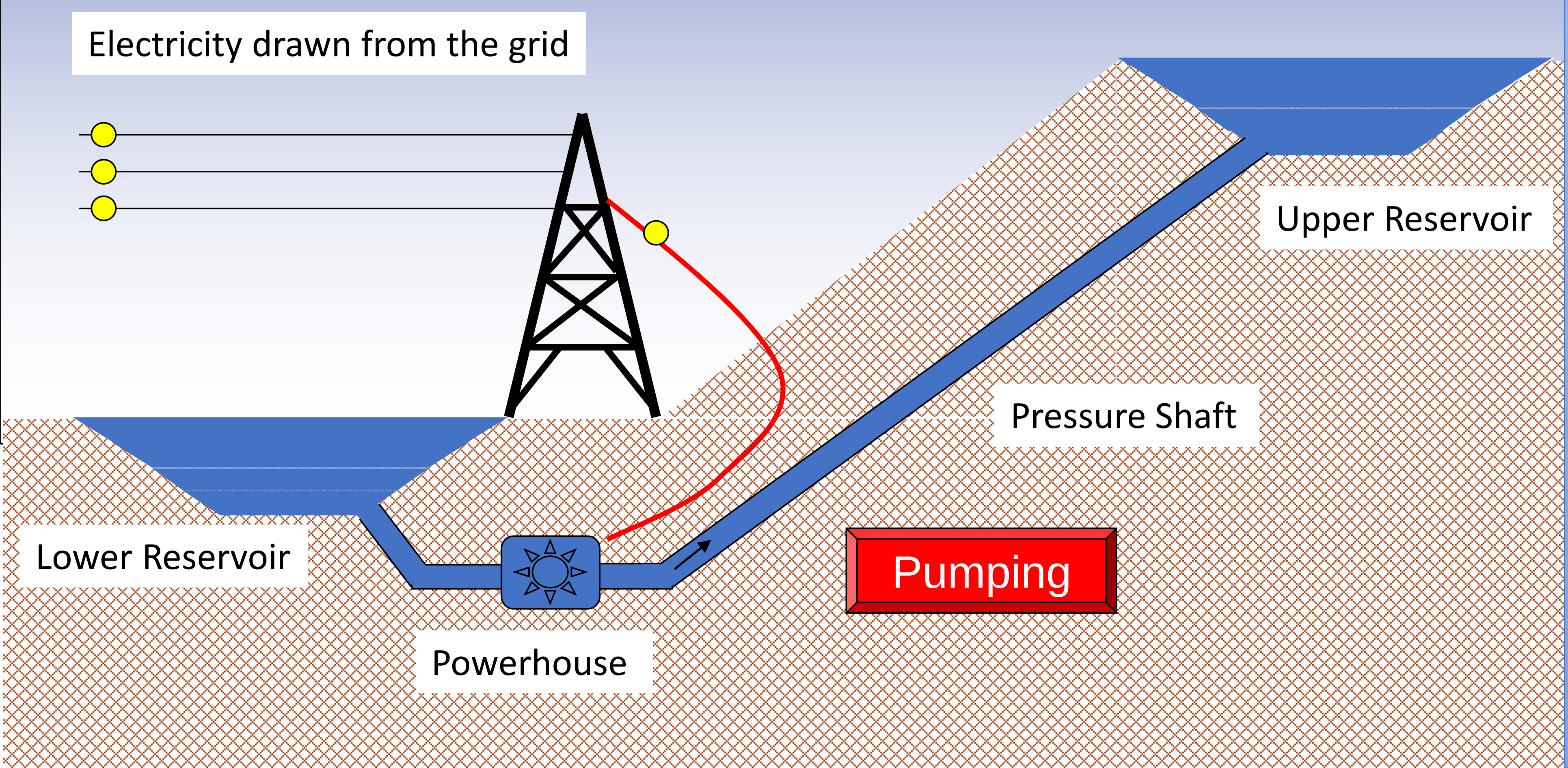
# What is Pumped Storage?

Pumped Storage is effectively a big rechargeable battery.

It is charged when there is surplus electricity.

It discharges when the stored electricity is needed.


# Pumped Storage - How Does it Work?

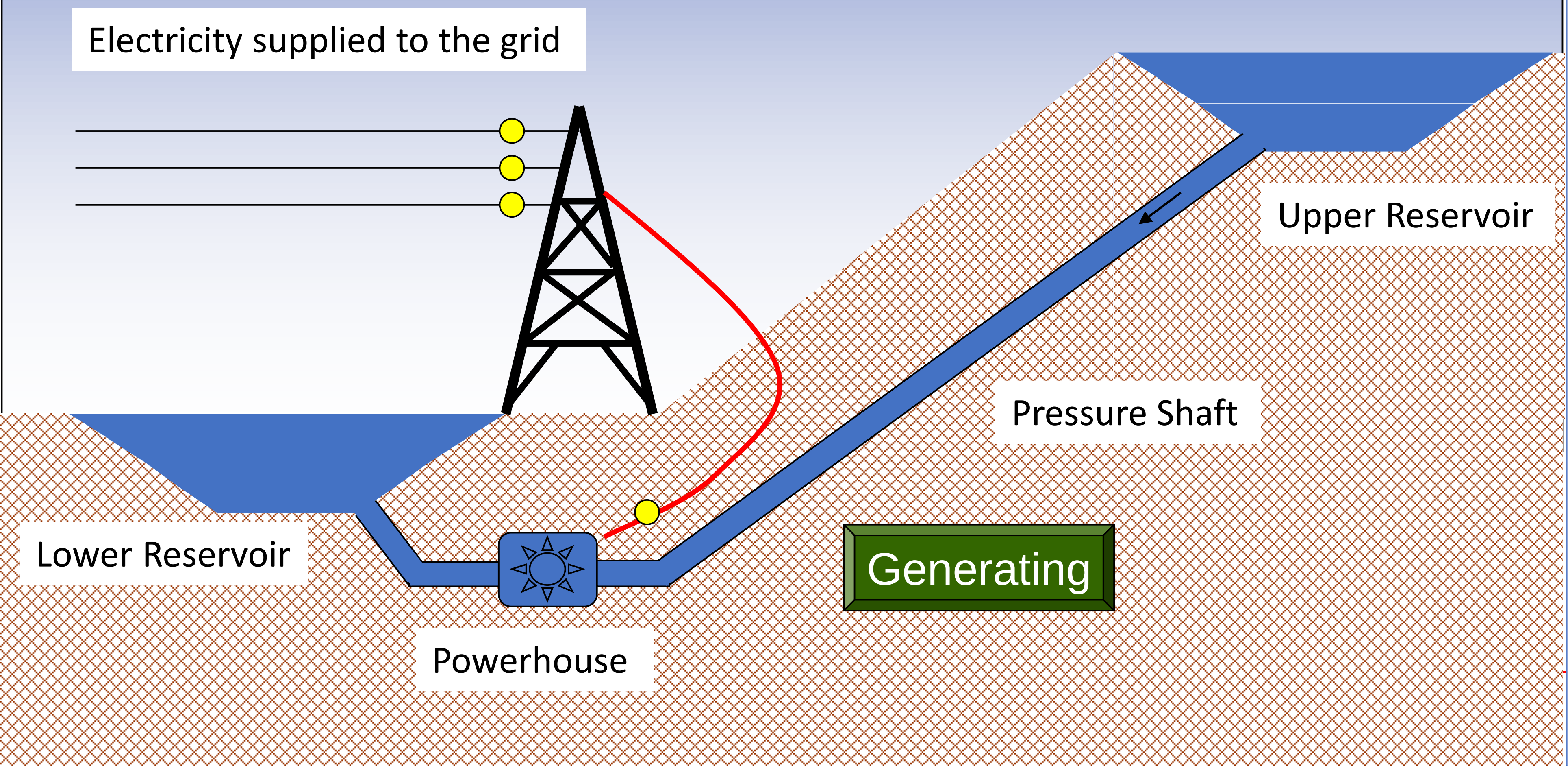



**Pumping Mode**

Surplus electricity is used to pump water up the hill, filling the upper storage reservoir.

Electricity is stored as potential energy.

# Pumped Storage - How Does it Work?




## Generating Mode

When electricity is needed, water is released from the upper reservoir, driving the turbines and creating electricity, which is exported to the grid.

# History of Pumped Storage

- Pumped storage first used in Europe in 1890s;
- Reversible pump-turbines developed in 1930s;
- Large-scale reversible pump-turbines in 1950s;
- Station sizes:
  - Pre-1950s: most stations under 100 MW
  - 1950 to 1965: many stations up to 300 MW
  - 1965 to date: many stations larger than 1000 MW
- A burst of PSP construction in 1960s to 1980s and considerable new capacity now planned.

# UK Pumped Storage Schemes

| Name | Owner | Date | Capacity |
|---|---|---|---|
| Dinorwig | First Hydro | 1984 | 1728 MW |
| Ffestiniog | First Hydro | 1963 | 360 MW |
| Cruachan | SP / Ibedrola | 1965 | 440 MW |
| Foyers | SSE | 1974 | 300 MW |
| TOTAL | | | 2828 MW |

GB's 30,000 MWh of storage provides around 10 hours of PSP generation, but only around **3% of average daily energy demand**.

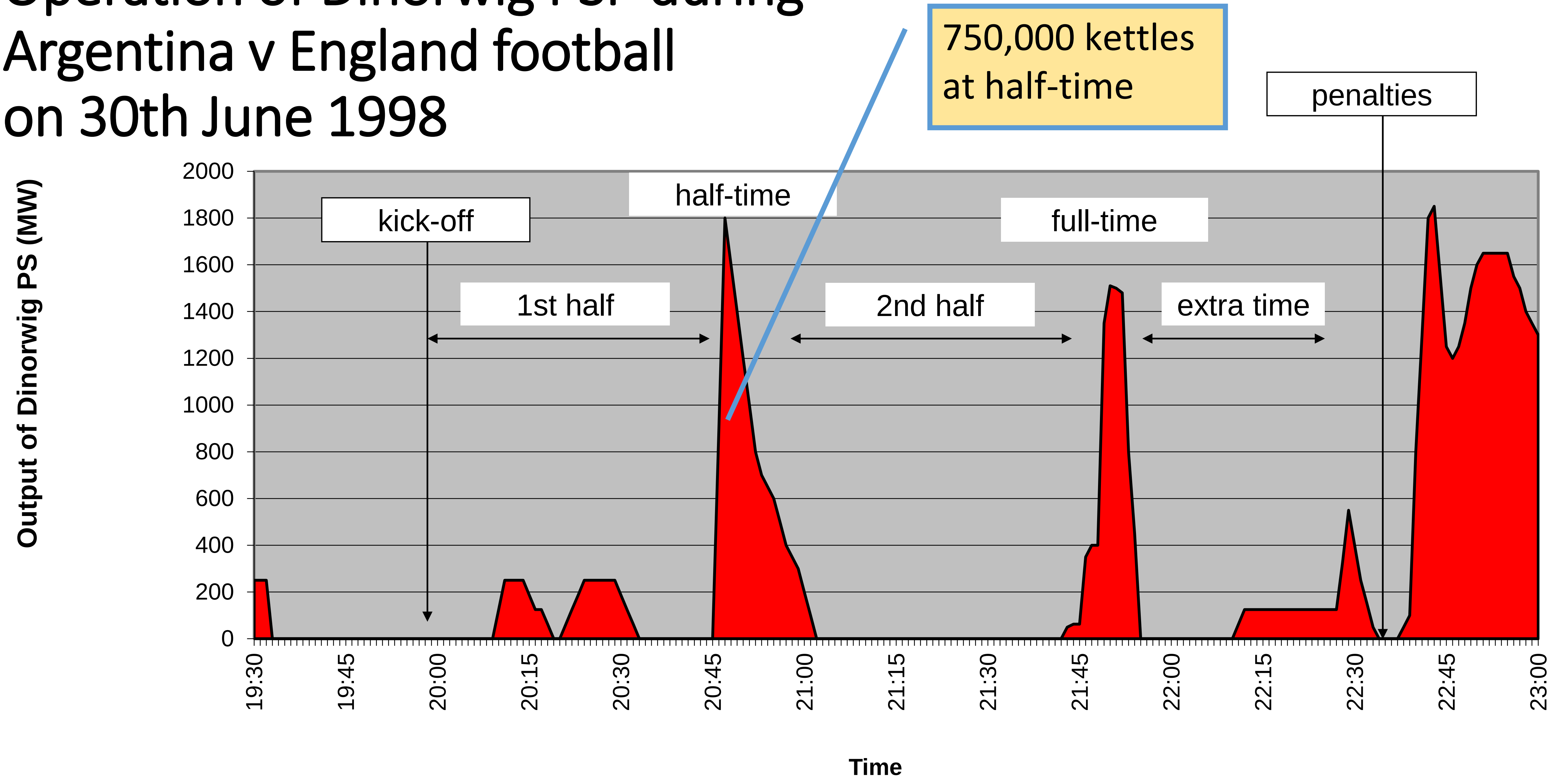
- Dinorwig has around 5 hours of storage capacity
- Ffestiniog and Cruachan each have around 20 hours of capacity

# Role of pumped storage

# Balancing Services by Pumped Storage

- Peak Shaving or Load Shaping: pumping off-peak and generating on-peak.
- Load pick-ups: very rapid response (<20 secs) to increased demand or loss of generation).
- Load following: variable output or input to match demand.
- Stand-by: quick response to loss of generation capacity.
- Firming intermittent generators (e.g. wind).
- Absorbing surplus power to avoid constraint payments.
- Power factor correction and voltage regulation.
- Blackstart of grid following blackout.

# Operation of Dinorwig PSP during Argentina v England football on 30th June 1998



# Future generation mix

| Technology | Constant | Predictable | Despatchable | Low Carbon |
|---|---|---|---|---|
| Nuclear | Yes | Yes | No | Yes |
| Hydroelectric with storage | (Yes) | (Yes) | Yes | Yes |
| Hydroelectric: run-of-river | No | No | (Yes) | Yes |
| Solar Photovoltaic | No | No | No | Yes |
| Solar Thermal | (Yes) | No | No | Yes |
| Wind | No | No | No | Yes |
| Tidal Stream | No | Yes | No | Yes |
| Tidal Range | No | Yes | (Yes) | Yes |
| Biomass / MSW | Yes | Yes | (Yes) | Yes |
| Geothermal | Yes | Yes | No | Yes |

Removing high carbon generation reduces constancy, predictability and most of all despatchability. **The system is difficult to operate without storage**.

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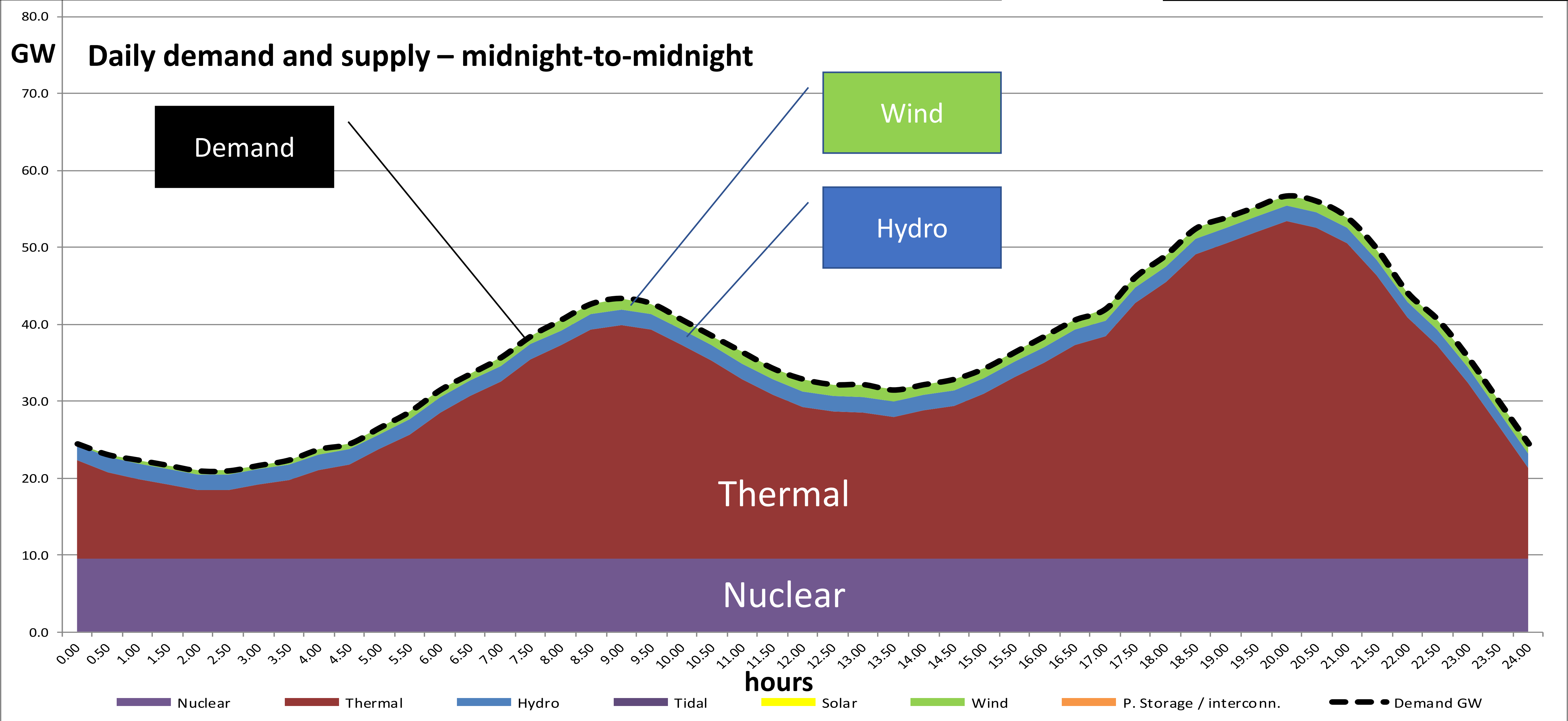
# How are Power Systems Changing?

- Intermittency and variability of generation means continually changing energy mix – difficult to manage, especially with uncontrolled generation.
- Need for more stop-starts, faster ramping, storage, stand-by generation, frequency regulation, interconnectors.
- System inertia – historically provided by large rotating plant – is becoming a major issue for the GB grid.

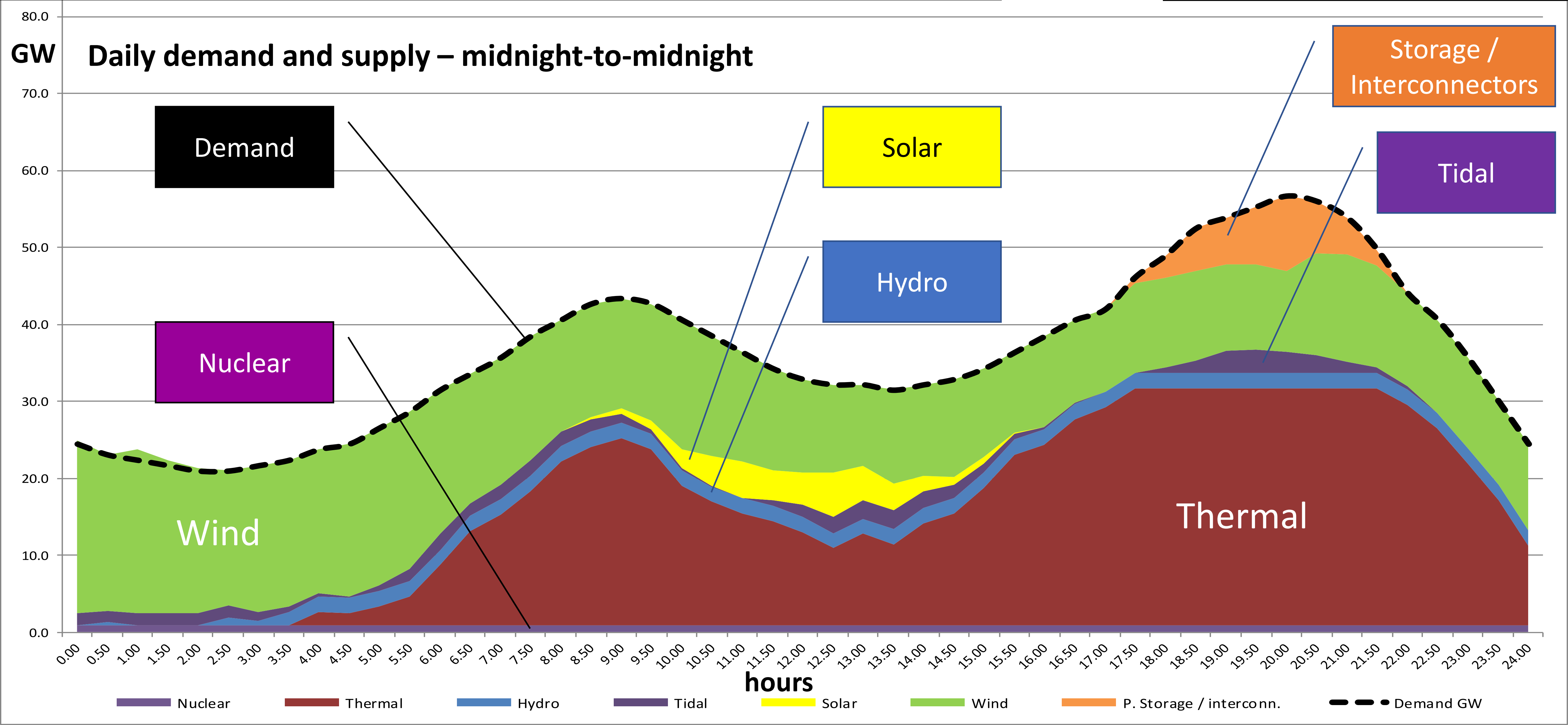
# Generation Despatch before significant renewables

# UK 2010 Winter Day



# Generation Despatch with more Renewables – High Wind Day

# UK 2025 Winter Day



# Generation Despatch with more Renewables – Low Wind Day

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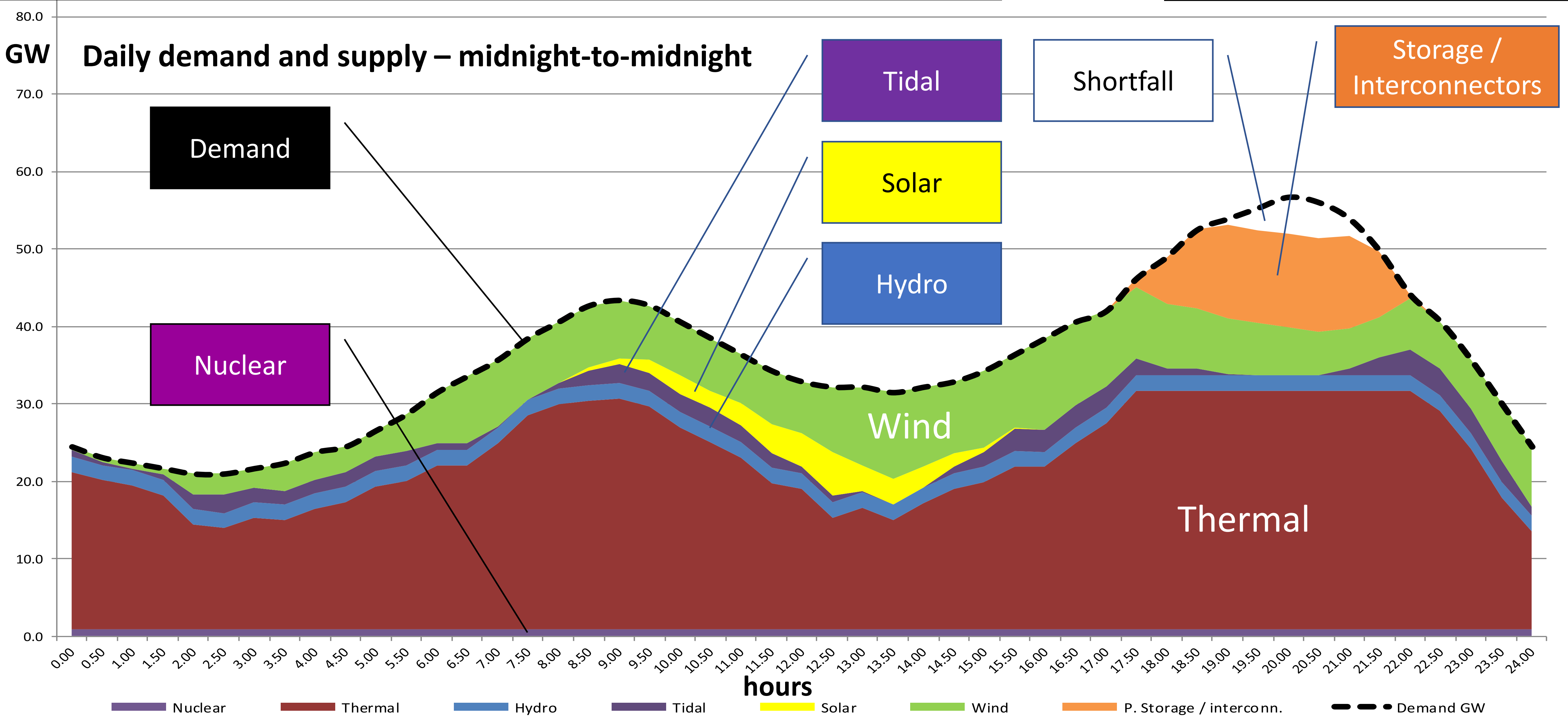
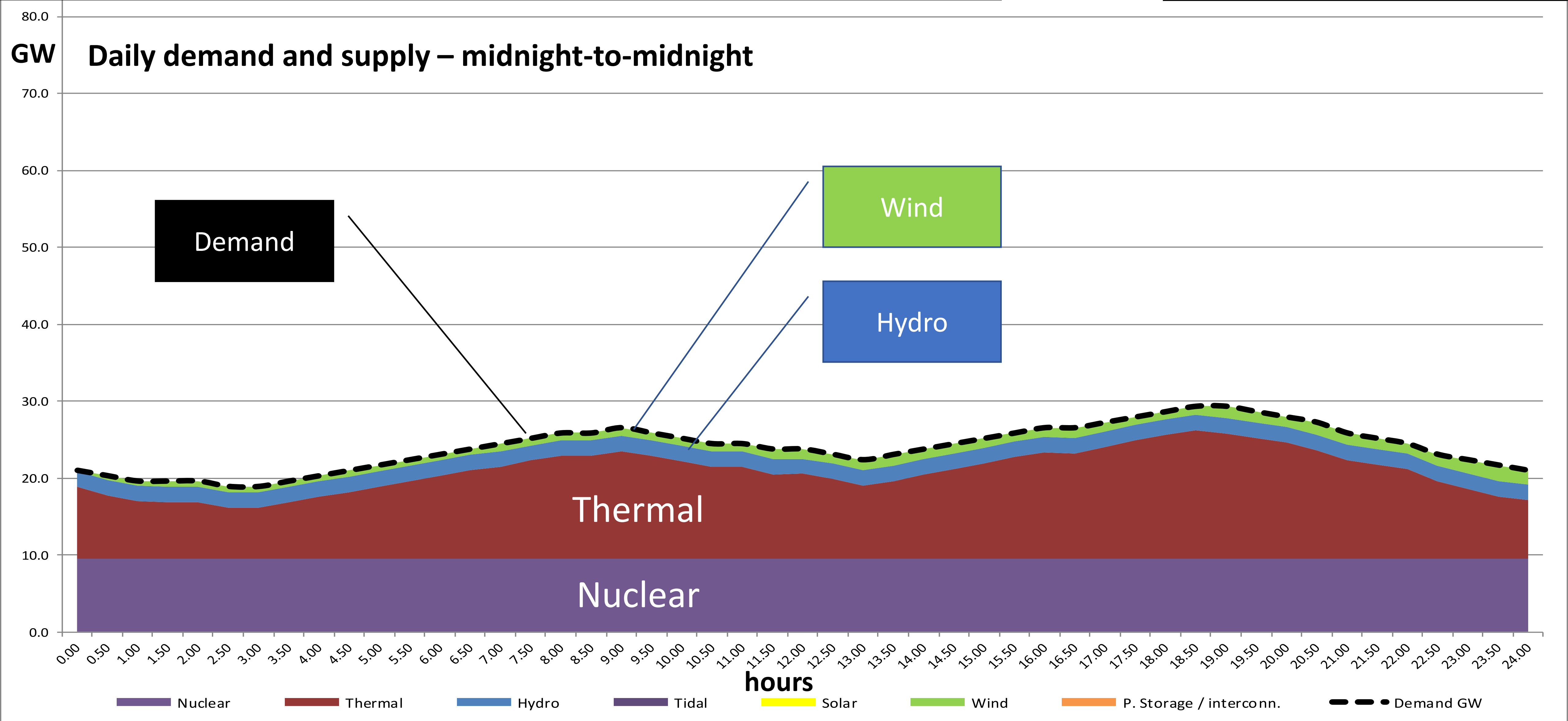


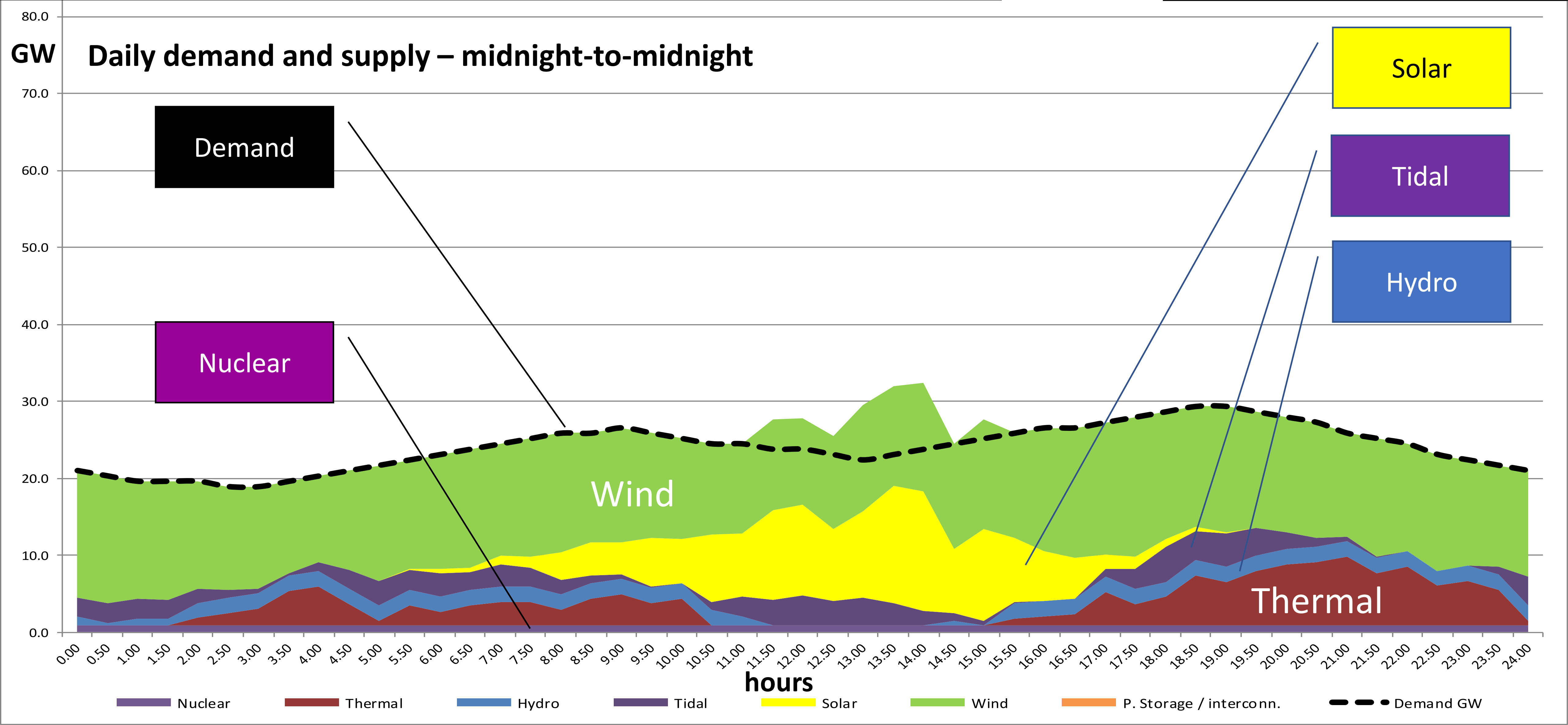
# Generation Despatch before significant renewables

# UK 2010 Summer Day



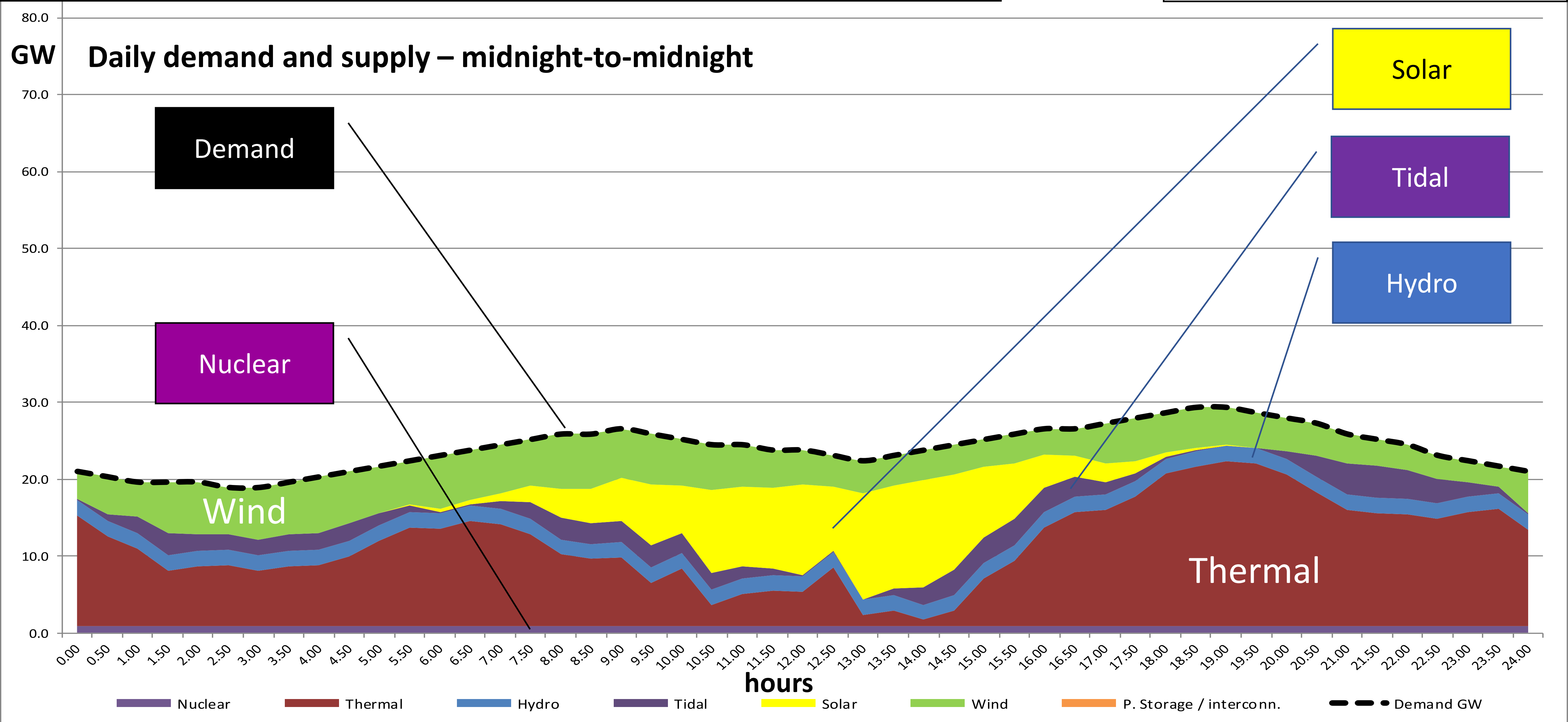
# Generation Despatch with more Renewables – High Wind Day

# UK 2025 Summer Day



# Generation Despatch with more Renewables – Low Wind Day

# UK 2025 Summer Day



# Ireland's DS3: 14 System Services

"Delivering a Secure, Sustainable Electricity System"

| Service Name | Abbrev. | Unit of Payment | Short Description |
|---|---|---|---|
| **Synchronous Inertial Response** | SIR | MWs2h | (Stored kinetic energy)*(SIR Factor – 15) |
| **Fast Frequency Response** | FFR | MWh | MW delivered between 2 and 10 seconds |
| **Primary Operating Reserve** | POR | MWh | MW delivered between 5 and 15 seconds |
| **Secondary Operating Reserve** | SOR | MWh | MW delivered between 15 to 90 seconds |
| **Tertiary Operating Reserve 1** | TOR1 | MWh | MW delivered between 90 seconds to 5 minutes |
| **Tertiary Operating Reserve 2** | TOR2 | MWh | MW delivered between 5 minutes to 20 minutes |
| **Replacement Reserve – Synchronised** | RRS | MWh | MW delivered between 20 minutes to 1 hour |
| **Replacement Reserve – Desynchronised** | RRD | MWh | MW delivered between 20 minutes to 1 hour |
| **Ramping Margin 1** | RM1 | MWh | The increased MW output that can be delivered with a good degree of certainty for the given time horizon. |
| **Ramping Margin 3** | RM3 | MWh | |
| **Ramping Margin 8** | RM8 | MWh | |
| **Fast Post Fault Active Power Recovery** | FPFAPR | MWh | Active power (MW) >90% within 250 ms of voltage >90% |
| **Steady State Reactive Power** | SSRP | Mvarh | (Mvar capability)*(% of capacity that Mvar capability is achievable) |
| **Dynamic Reactive Response** | DRR | MWh | MVAr capability during large (>30%) voltage dips |

# Ireland’s DS3: % of each service by generation technology

| Service: | Capacity | SIR | FFR | POR | SOR | TOR1 | TOR2 | RR (S) | RR (D) | RM1 | RM3 | RM8 | SSRP | DRR | FPFAPR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Technology** | % | % | % | % | % | % | % | % | % | % | % | % | % | % | % |
| Combined Cycle Gas Turbine | 41% | 21% | 15% | 22% | 23% | 27% | 26% | 37% | 0% | 0% | 0% | 27% | 37% | 47% | 45% |
| Combined Heat and Power | 2% | 0% | 0% | 1% | 0% | 1% | 2% | 3% | 0% | 0% | 7% | 5% | 1% | 2% | 2% |
| Demand Side Management | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 6% | 9% | 3% | 2% | 0% | 0% | 0% |
| Hydropower (conventional) | 2% | 1% | 0% | 0% | 1% | 2% | 4% | 3% | 8% | 7% | 7% | 5% | 3% | 2% | 2% |
| Interconnector (with UK) | 7% | 0% | 65% | 48% | 37% | 34% | 30% | 13% | 39% | 30% | 29% | 21% | 6% | 0% | 5% |
| Open Cycle Gas Turbine | 10% | 12% | 8% | 12% | 12% | 12% | 14% | 20% | 33% | 43% | 42% | 30% | 14% | 12% | 11% |
| Pumped Storage-Turlough Hill | 3% | 18% | 3% | 5% | 14% | 12% | 12% | 5% | 15% | 12% | 11% | 8% | 5% | 3% | 3% |
| Thermal -coal, peat, oil & gas | 29% | 48% | 8% | 12% | 12% | 12% | 12% | 17% | 0% | 0% | 1% | 3% | 31% | 34% | 32% |
| Wind | 6% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 3% | 0% | 0% |
| **Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

# Ireland's DS3: % of each service by generation technology

| | Better than 120% | | Between 80% and 120% | | Less than 80% |
|---|---|---|---|---|---|

| Service: | Capacity | SIR | FFR | POR | SOR | TOR1 | TOR2 | RR (S) | RR (D) | RM1 | RM3 | RM8 | SSRP | DRR | FPFAPR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Technology** | % | % | % | % | % | % | % | % | % | % | % | % | % | % | % |
| Combined Cycle Gas Turbine | 41% | 21% | 15% | 22% | 23% | 27% | 26% | 37% | 0% | 0% | 0% | 27% | 37% | 47% | 45% |
| Combined Heat and Power | 2% | 0% | 0% | 1% | 0% | 1% | 2% | 3% | 0% | 0% | 7% | 5% | 1% | 2% | 2% |
| Demand Side Management | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 6% | 9% | 3% | 2% | 0% | 0% | 0% |
| Hydropower (conventional) | 2% | 1% | 0% | 0% | 1% | 2% | 4% | 3% | 8% | 7% | 7% | 5% | 3% | 2% | 2% |
| Interconnector (with UK) | 7% | 0% | 65% | 48% | 37% | 34% | 30% | 13% | 39% | 30% | 29% | 21% | 6% | 0% | 5% |
| Open Cycle Gas Turbine | 10% | 12% | 8% | 12% | 12% | 12% | 14% | 20% | 33% | 43% | 42% | 30% | 14% | 12% | 11% |
| Pumped Storage-Turlough Hill | 3% | 18% | 3% | 5% | 14% | 12% | 12% | 5% | 15% | 12% | 11% | 8% | 5% | 3% | 3% |
| Thermal -coal, peat, oil & gas | 29% | 48% | 8% | 12% | 12% | 12% | 12% | 17% | 0% | 0% | 1% | 3% | 31% | 34% | 32% |
| Wind | 6% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 3% | 0% | 0% |
| **Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

# When thermal generation disappears (within a few years)

| | Better than 120% | | Between 80% and 120% | | Less than 80% |
|---|---|---|---|---|---|

| Service: | Capacity | SIR | FFR | POR | SOR | TOR1 | TOR2 | RR (S) | RR (D) | RM1 | RM3 | RM8 | SSRP | DRR | FPFAPR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Technology** | % | % | % | % | % | % | % | % | % | % | % | % | % | % | % |
| Combined Cycle Gas Turbine | 57% | 41% | 16% | 25% | 26% | 30% | 30% | 44% | 0% | 0% | 0% | 28% | 54% | 71% | 65% |
| Combined Heat and Power | 2% | 0% | 0% | 1% | 0% | 1% | 3% | 4% | 0% | 0% | 7% | 5% | 2% | 3% | 3% |
| Demand Side Management | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 6% | 9% | 3% | 2% | 0% | 0% | 0% |
| Hydropower (conventional) | 3% | 2% | 0% | 0% | 1% | 3% | 4% | 4% | 8% | 7% | 7% | 5% | 4% | 4% | 3% |
| Interconnector (with UK) | 10% | 0% | 71% | 55% | 43% | 39% | 34% | 16% | 39% | 30% | 30% | 21% | 8% | 0% | 8% |
| Open Cycle Gas Turbine | 15% | 23% | 9% | 14% | 14% | 14% | 16% | 24% | 33% | 43% | 43% | 31% | 20% | 18% | 17% |
| Pumped Storage-Turlough Hill | 4% | 34% | 4% | 6% | 15% | 14% | 13% | 6% | 15% | 12% | 12% | 8% | 7% | 5% | 4% |
| Wind | 8% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

# Three different roles for PSP

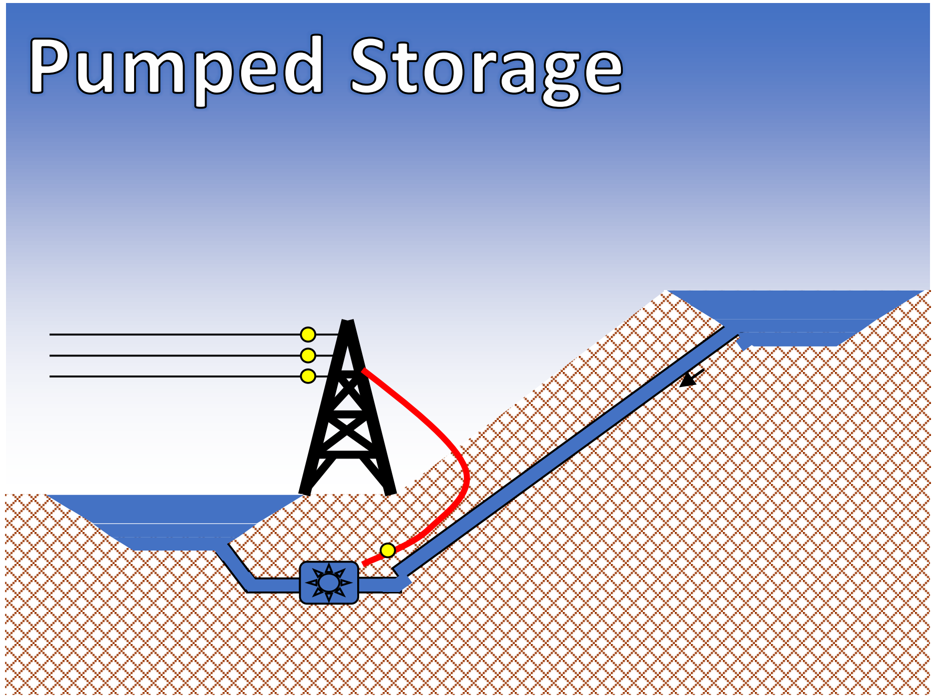
- **Bulk Energy Storage**
  Storage of energy to make up for shortfalls in supply due to prolonged spells of low wind and solar generation. Schemes can be located anywhere there is good topography (sites for reservoirs and high head) providing there is transmission capacity.

- **System support**
  Ability to rapidly inject or absorb active or reactive capacity into the grid, provide system inertia and other ancillary services. Location can be important for grid stability.

- **Alleviating transmission constraints**
  Near demand centres and/or near supply centres, can avoid overloading transmission lines and interconnectors.

# Chemical or Water Storage?


OR



# Chemical or Water: Scale Comparison

## <u>Hornsdale Power Reserve</u>

(Tesla Big Battery), South Australia

- Largest battery storage in world
- 100 MW
- 129 MWh
- USD 65 m
- Life: 20 years?

## <u>Snowy 2 Pumped Storage</u>

In planning, New South Wales

- Two existing reservoirs, 27 km apart
- 2000 MW (20 x)
- 350,000 MWh (2700 x)
- ~USD 4 bn (60 x)
- Life: 100 years? (5 x)

SSE's proposed Coire Glas PSP in Scotland has 1500 MW capacity and 30,000 MWh storage

# Batteries and PSP have different characteristics

## Chemical (batteries)

- Very rapid injection (<1sec)
- Quick to build and low risk
- Cheap for capacity (MW)
- Significant fire hazard
- Degrades with use
- Poor sustainability
- Can be installed where needed

## Water (pumped storage)

- Fast ramping (full output <20sec)
- Provides system inertia
- Cheap for energy (MWh)
- Proven technology
- Long life (> 100 years)
- Good sustainability
- Depends on a good site

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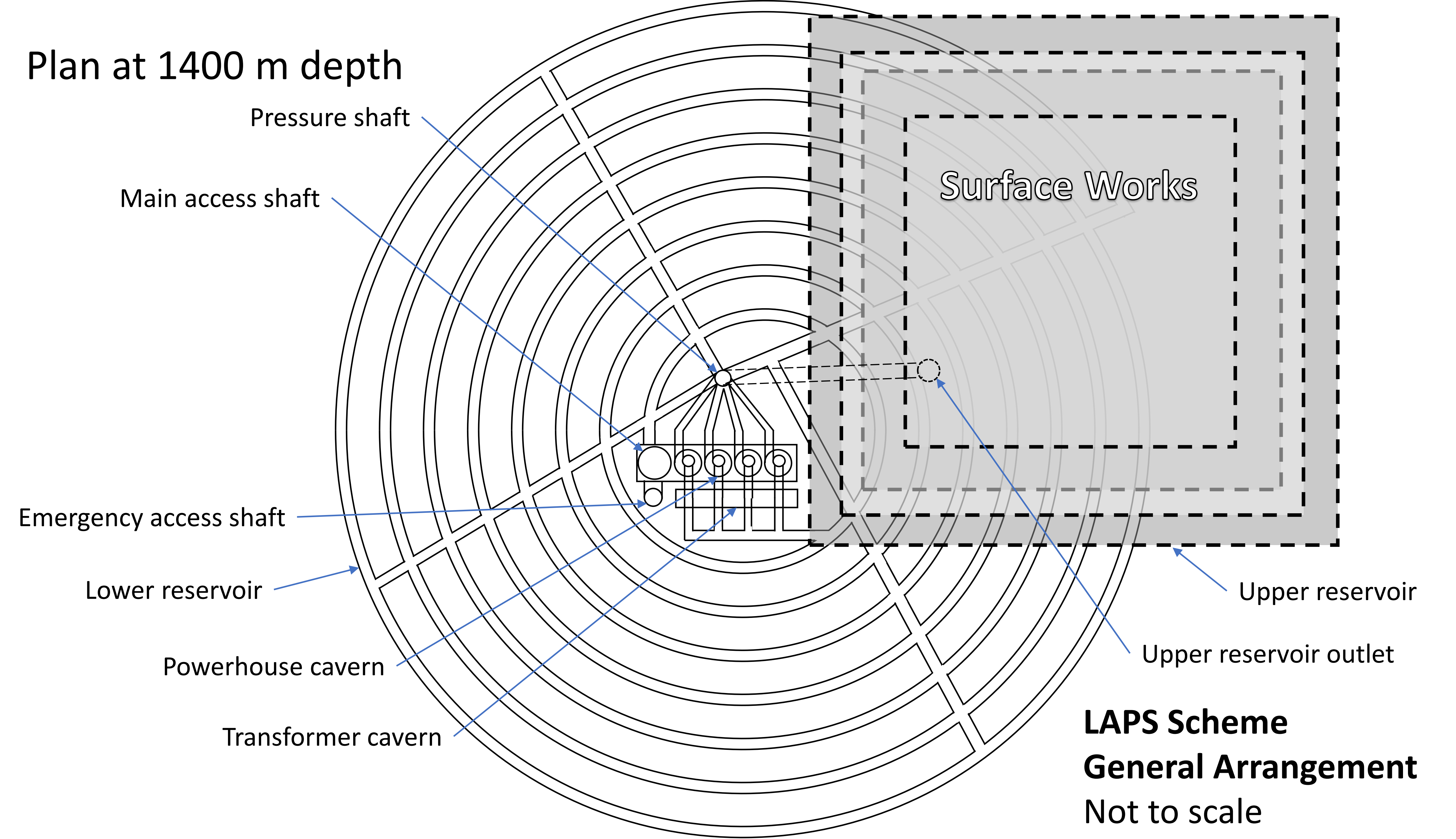
# Location-agnostic Pumped Storage (LAPS)

Developed with my colleagues at **Mott MacDonald** to enable low-cost, system-supporting pumped storage to be constructed at almost any location required by the grid.

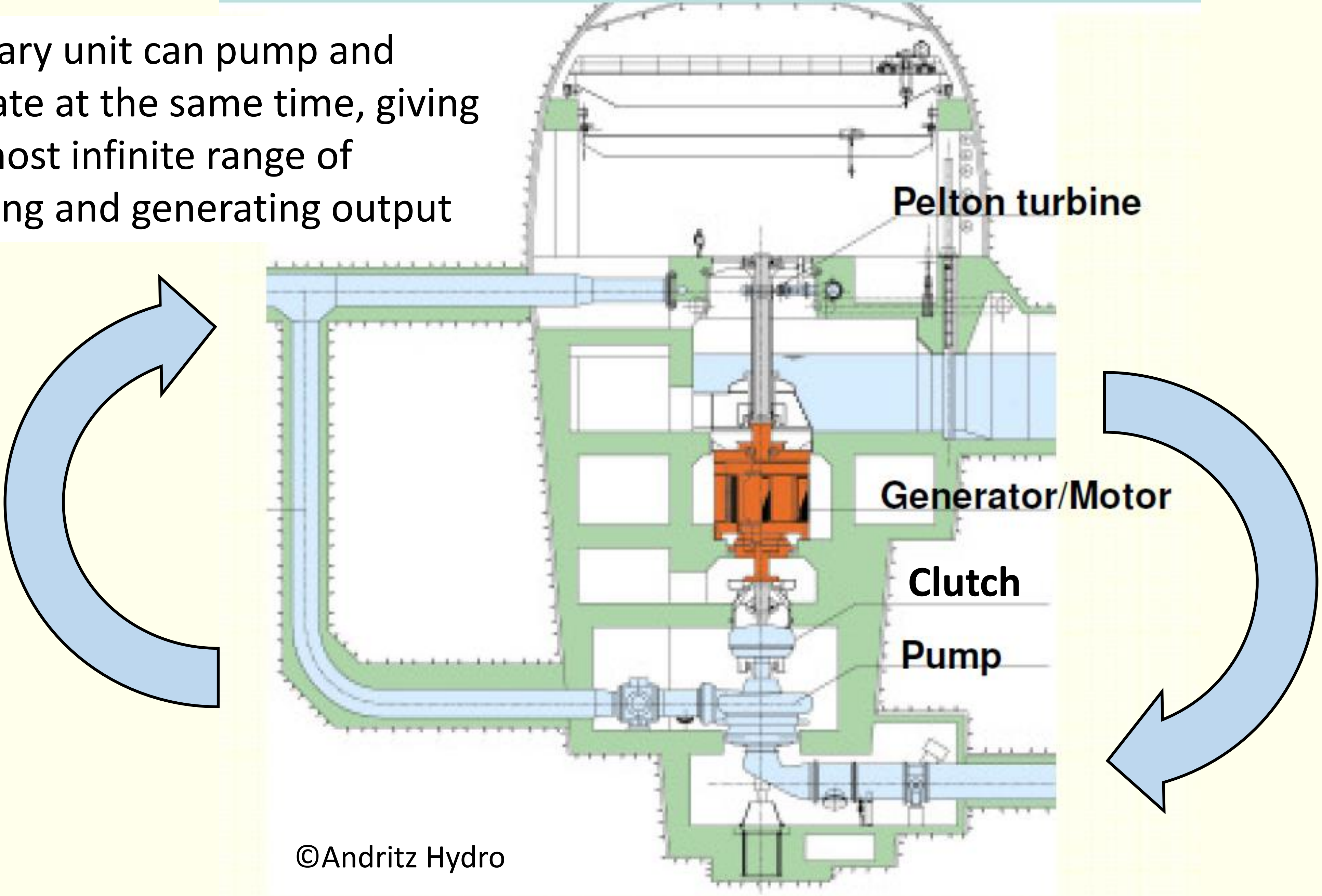
The concept uses recent developments in shaft-sinking, tunnelling and turbine-generator design to produce a modular scheme that will meet many of the new challenges faced by System Operators.



Plan at 1400 m depth
Pressure shaft
Main access shaft
Surface Works
Emergency access shaft
Lower reservoir
Upper reservoir
Upper reservoir outlet
Powerhouse cavern
Transformer cavern
LAPS Scheme
General Arrangement
Not to scale

# Ternary unit

A ternary unit can pump and generate at the same time, giving an almost infinite range of pumping and generating output

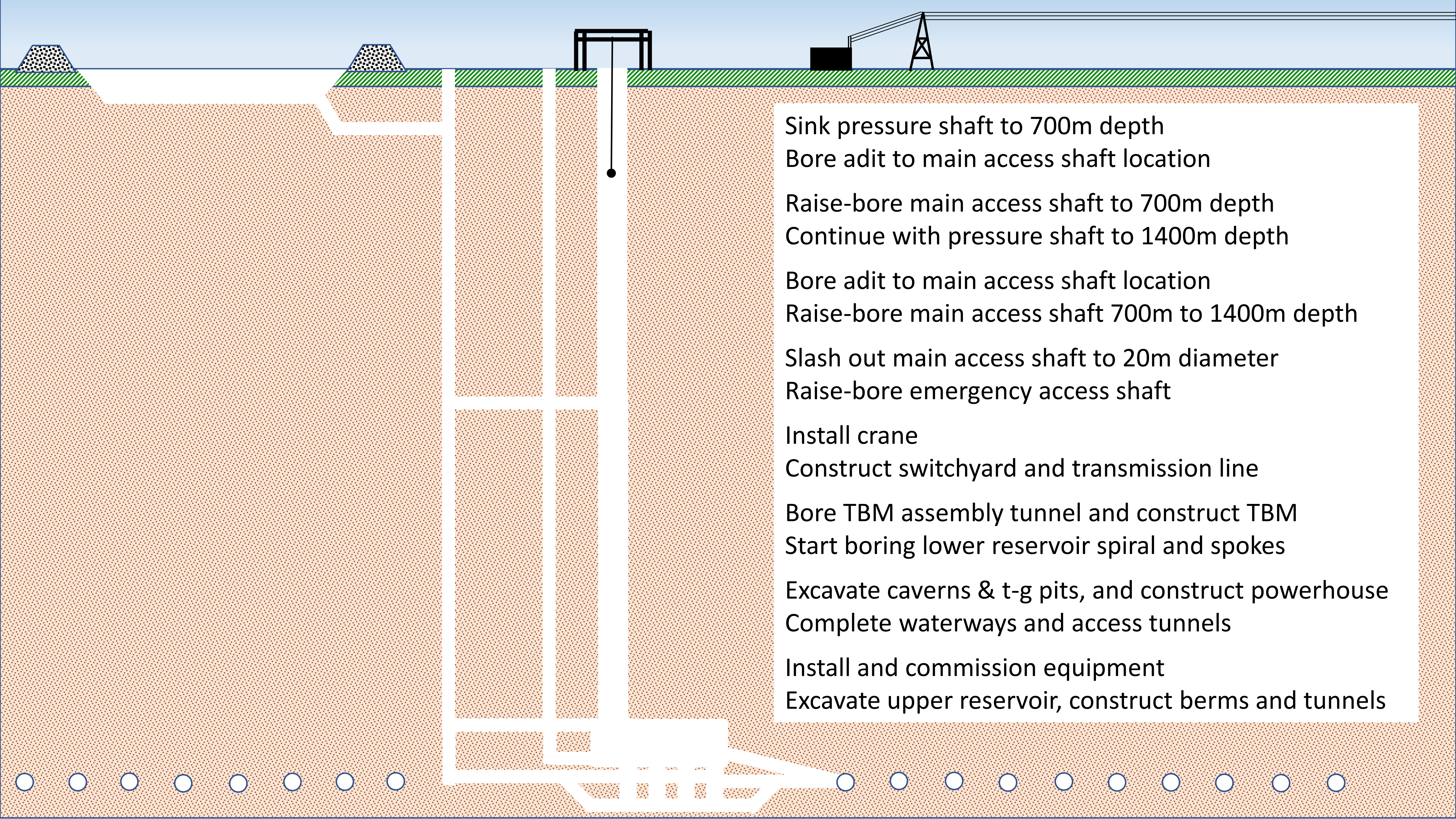


# Characteristics of LAPS

- Ultra-high head (1400 metres) means small storage volumes, small waterways and small t-g units for economy
- Mechanised shaft sinking, raised boring and TBM tunnelling allow reasonably rapid construction of civil works (generation within 5 years)
- Ternary unit (separate Pelton turbine and pump on common shaft with generator/motor) and hydraulic short circuit allows flexibility in pumping and generating, with rapid cycle changes (pump → generate → pump) and large system inertia.
- Closed system with no river impoundment, for easy licensing.

# Characteristics of LAPS Project (basic project)

| | |
|---|---|
| Installed capacity | 1000 MW |
| Energy storage | 6000 MWh (6 hours of generation / 7.5 hours of pumping) |
| Gross head | 1400 metres |
| Surface footprint | 50 to 100 ha |
| Water storage | 1.8 million cubic metres |
| Surface reservoir area | ~10 ha |
| Lower reservoir | 46 km of 7.0 m diameter TBM bored tunnel |
| Pumped-storage units | Pelton ternary units with multi-stage pumps and hydraulic short circuit |
| Scheme cycle efficiency | ~80% (90% generating, 89% pumping) |
| System regulating range | 2000 MW (1000 MW injection; 1000 MW absorption) |
| Zero (spinning) to pumping or turbining | Less than 30 seconds |
| Change from pumping to turbining (and v-v) | Less than 30 seconds |



Sink pressure shaft to 700m depth
Bore adit to main access shaft location

Raise-bore main access shaft to 700m depth
Continue with pressure shaft to 1400m depth

Bore adit to main access shaft location
Raise-bore main access shaft 700m to 1400m depth

Slash out main access shaft to 20m diameter
Raise-bore emergency access shaft

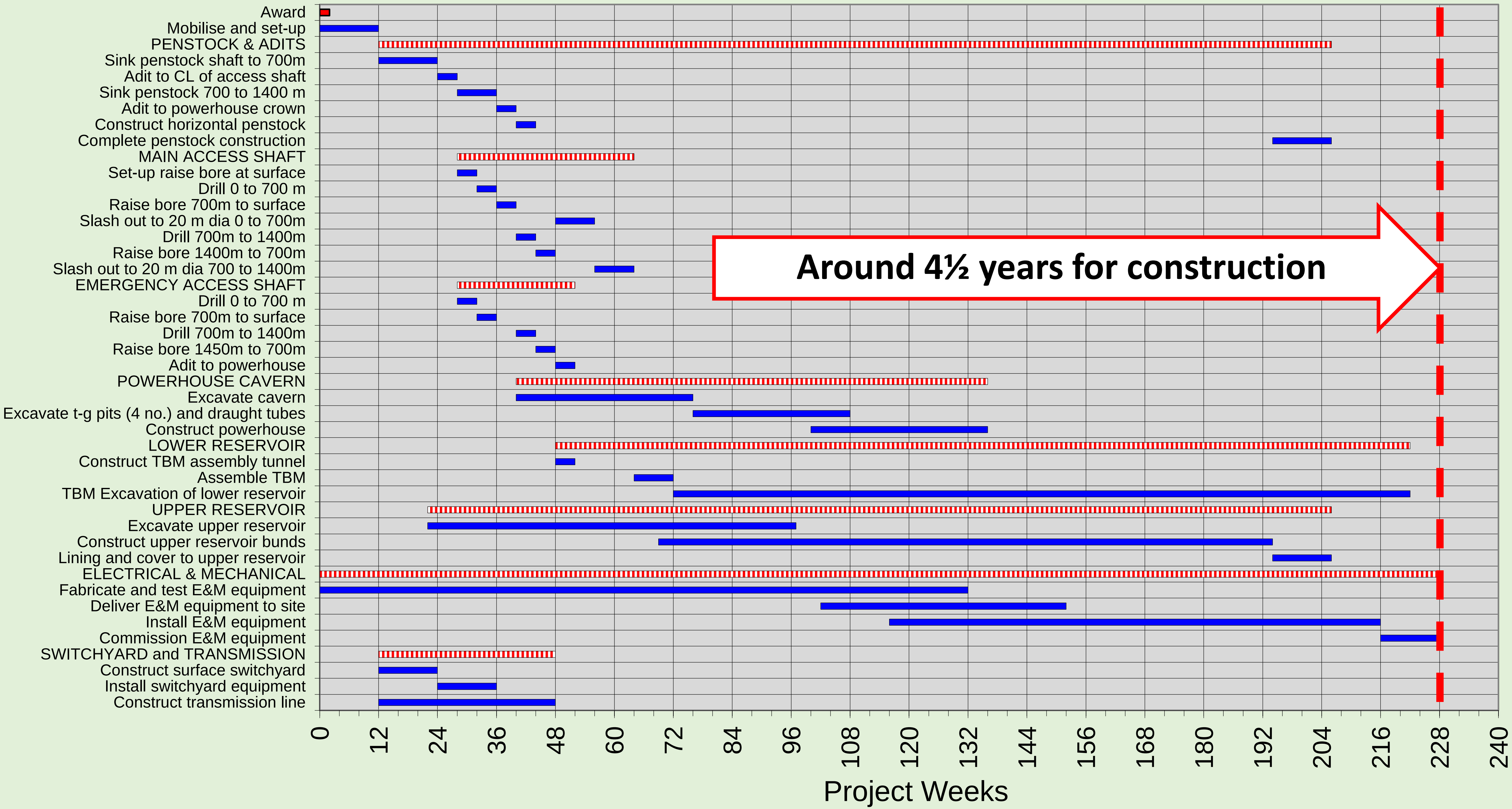
Install crane
Construct switchyard and transmission line

Bore TBM assembly tunnel and construct TBM
Start boring lower reservoir spiral and spokes

Excavate caverns & t-g pits, and construct powerhouse
Complete waterways and access tunnels

Install and commission equipment
Excavate upper reservoir, construct berms and tunnels

# Construction schedule for LAPS



# Construction Cost of LAPS Project
## 1000MW, 1400m depth, 6-hour storage (Class 5 estimate)

| | |
|---|---|
| Mobilisation | 40 USDm |
| Surface works | 55 USDm |
| Underground civil works | 640 USDm |
| Powerhouse equipment | 180 USDm |
| Switchyard and transmission | 20 USDm |
| Unmeasured items | 185 USDm |
| Contingencies | 225 USDm |
| **Total EPC cost** | **1,345 USDm** |
| Developer's costs | 400 USDm |
| **Total project cost excluding IDC** | **1,745 USDm** |
| Cost per kW of capacity | 1,745 USD/kW |
| Cost per kWh of energy storage | 290 USD/kWh |
| Marginal cost of additional storage | 120 USD/kWh |

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# LAPSAB: Adding batteries for even greater flexibility

- Pumped storage responds relatively quickly (<30 secs) to changes in supply or demand.  However it is not fast enough to control RoCoF.
- Running in synchronous condenser mode and stop-starts significantly increase maintenance requirements
- Adding 10 minutes of battery capacity (i.e. 1000 MW, 167 MWh) provides sub-second response, and fewer changes in output for LAPS.
- Cost of this battery installation should be less than USD 100m.
- Batteries can provide system support from end of Year 2 of construction.

# Environmental benefits of LAPS

- Closed loop, off-river and small surface footprint means low impacts and good sustainability – should be easy to license.
- Covered and lined surface reservoir limits water loss and make-up requirements.
- Ultra-high head means very little water required (< 2 mcm) for initial fill – use of desalinated water is possible if other sources not available.
- System support provided by LAPS / LAPSAB facilitates decarbonisation of the electricity grid with renewable generation (solar, wind and marine).

# How to finance a LAPS Project?

- Auction of ancillary services with multiple revenue streams is unlikely to be possible, and would lead to a very inefficient system.
- Much more planning of the grid infrastructure is now needed.
- The System Operator (SO) should commission grid support infrastructure as with transmission lines and substations.
- FELT Model (Finance, Engineer, Lease and Transfer)
  - enables SO to specify project requirements and location
  - allows private sector to be responsible for delivery
  - commercial finance is deployed
  - LAPS project reverts to public ownership at end of FELT term.

# Summary: Advantages of LAPS with FELT

- Future power system requires many ancillary services for security and stability, and location is important (cf DS3).
- LAPS multi-function pumped storage – constructed anywhere.
- With batteries (10 minute, 1000 MW) provides huge flexibility.
- Ultra-high head mean small storage and water requirement.
- FELT allows System Operator to specify and procure projects.
- FELT allows private sector to finance and deliver LAPS / LAPSAB.

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# Thank you

See **www.mcw-e.com** for more information about FELT financing model


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