ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

WIRE
Wind Engineering & Renewable Energy Laboratory

Wind Energy: Atmosphere to Electrons

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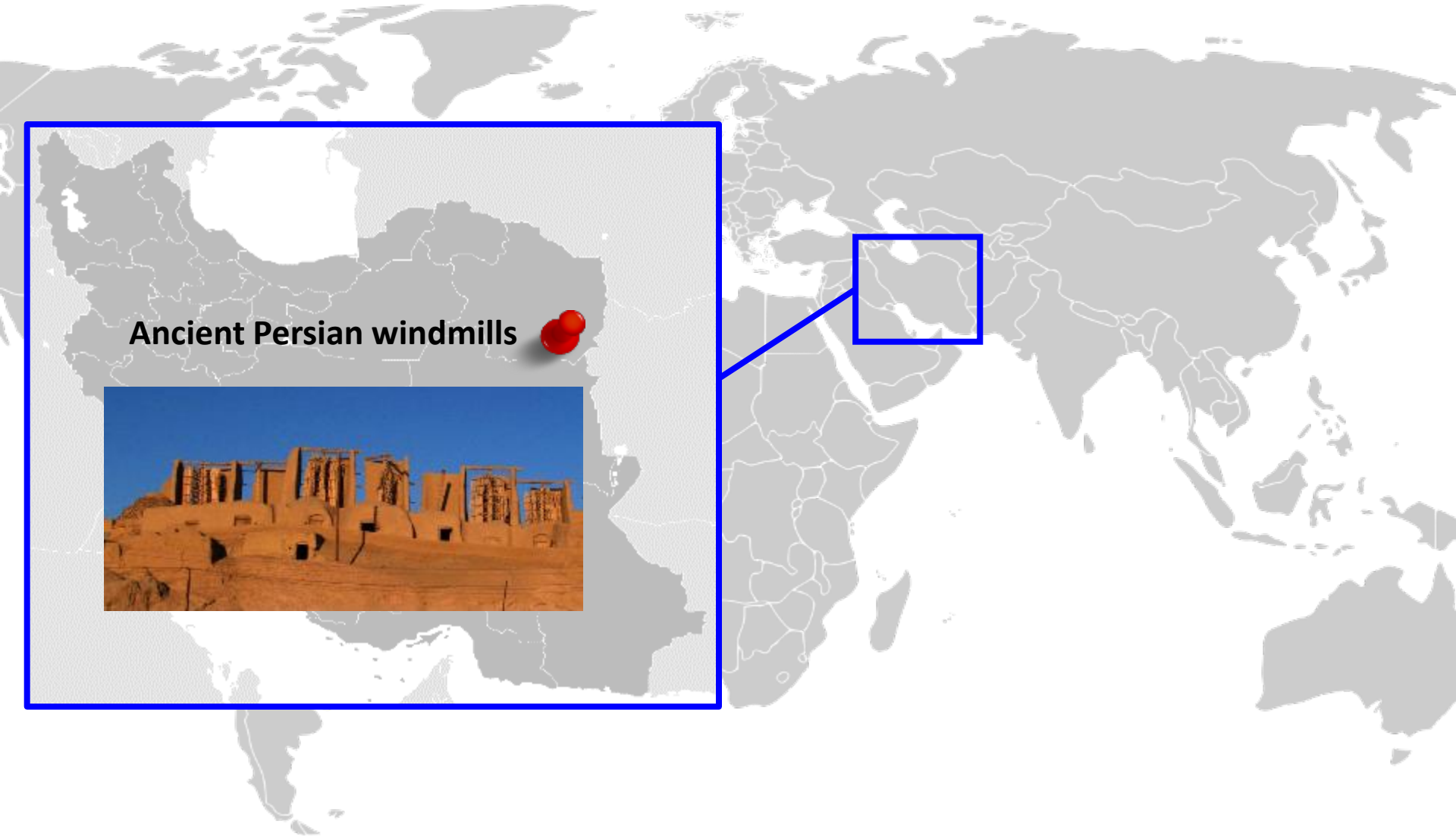
SCCER School "Shaping the Energy Transition" in Engelberg, 17.-20.10.2017

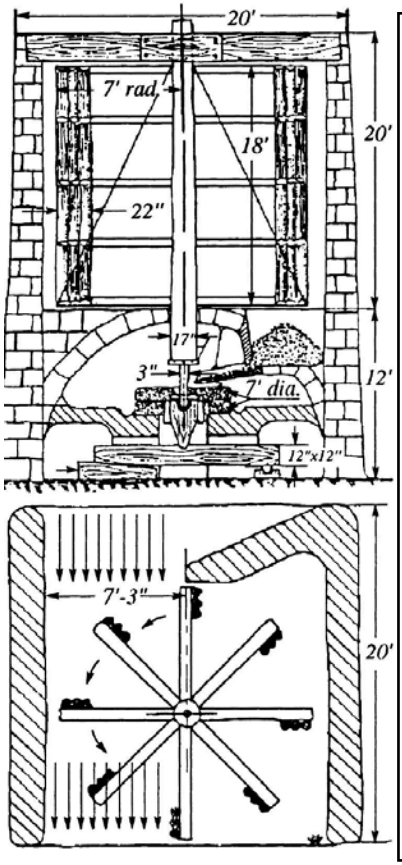
Historical Development

(Wind turbine technology, *Spera* 2009)

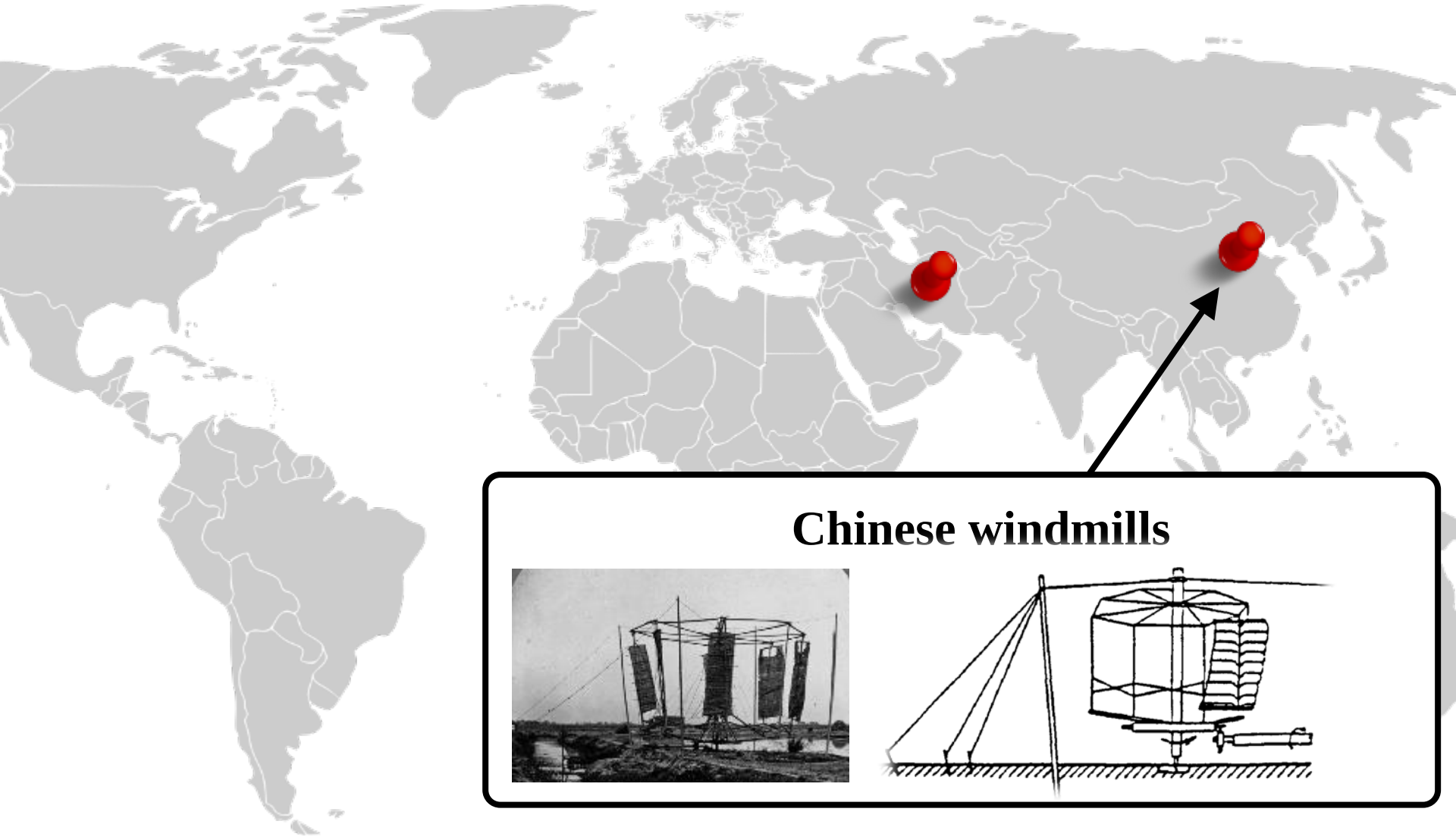
Historical Development



Historical Development



Historical Development

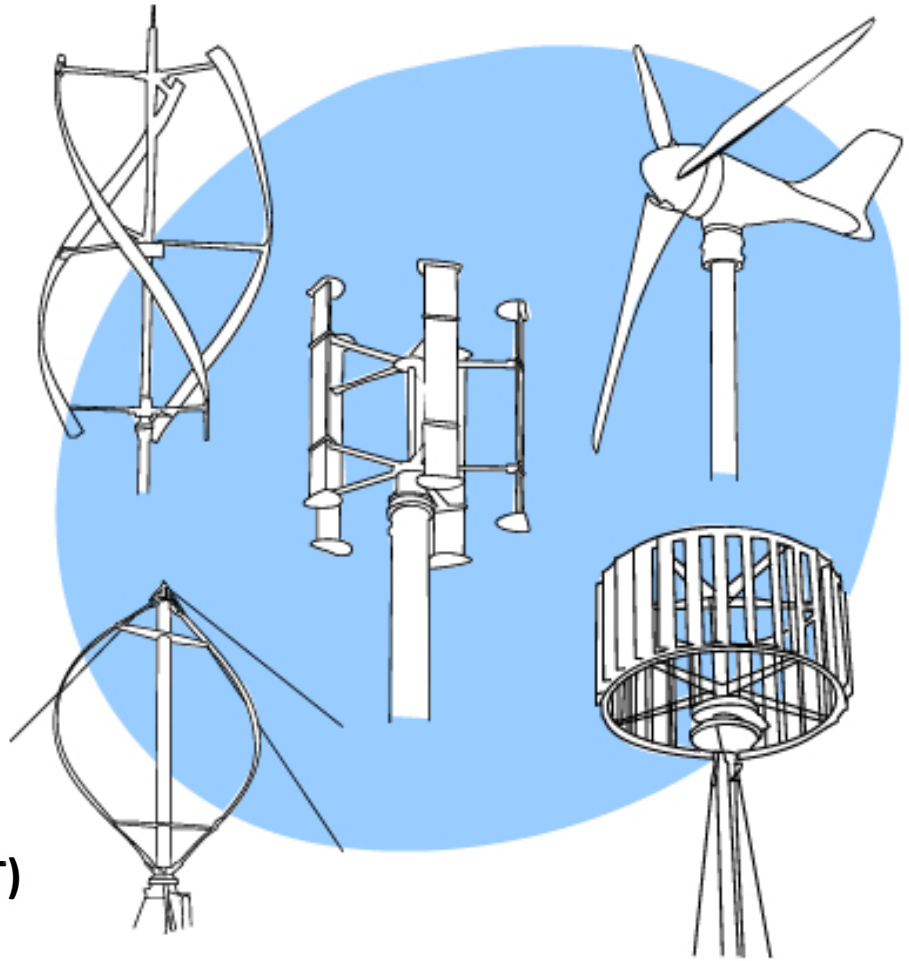


Chinese windmills

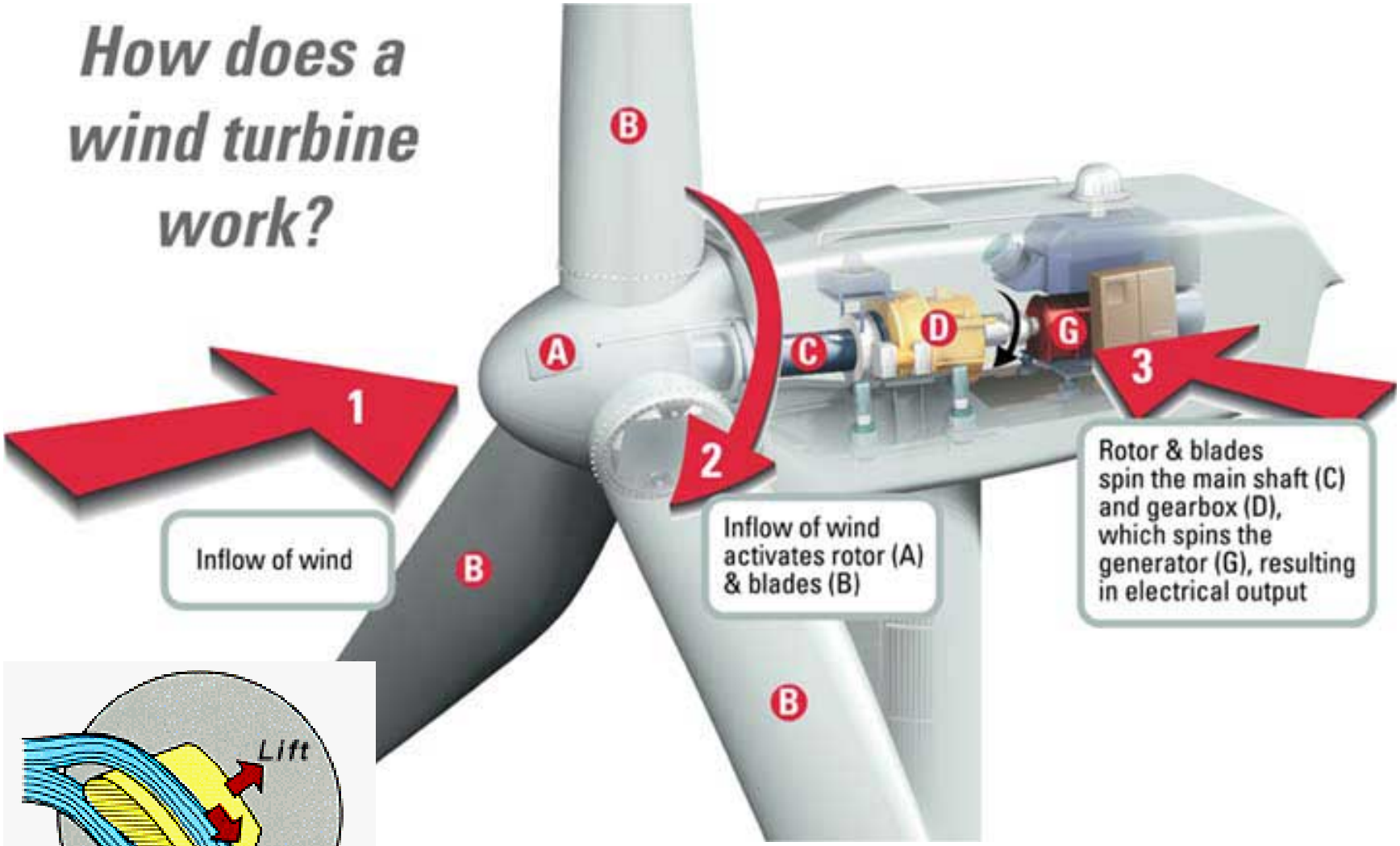
Historical Development

Modern Wind Turbines

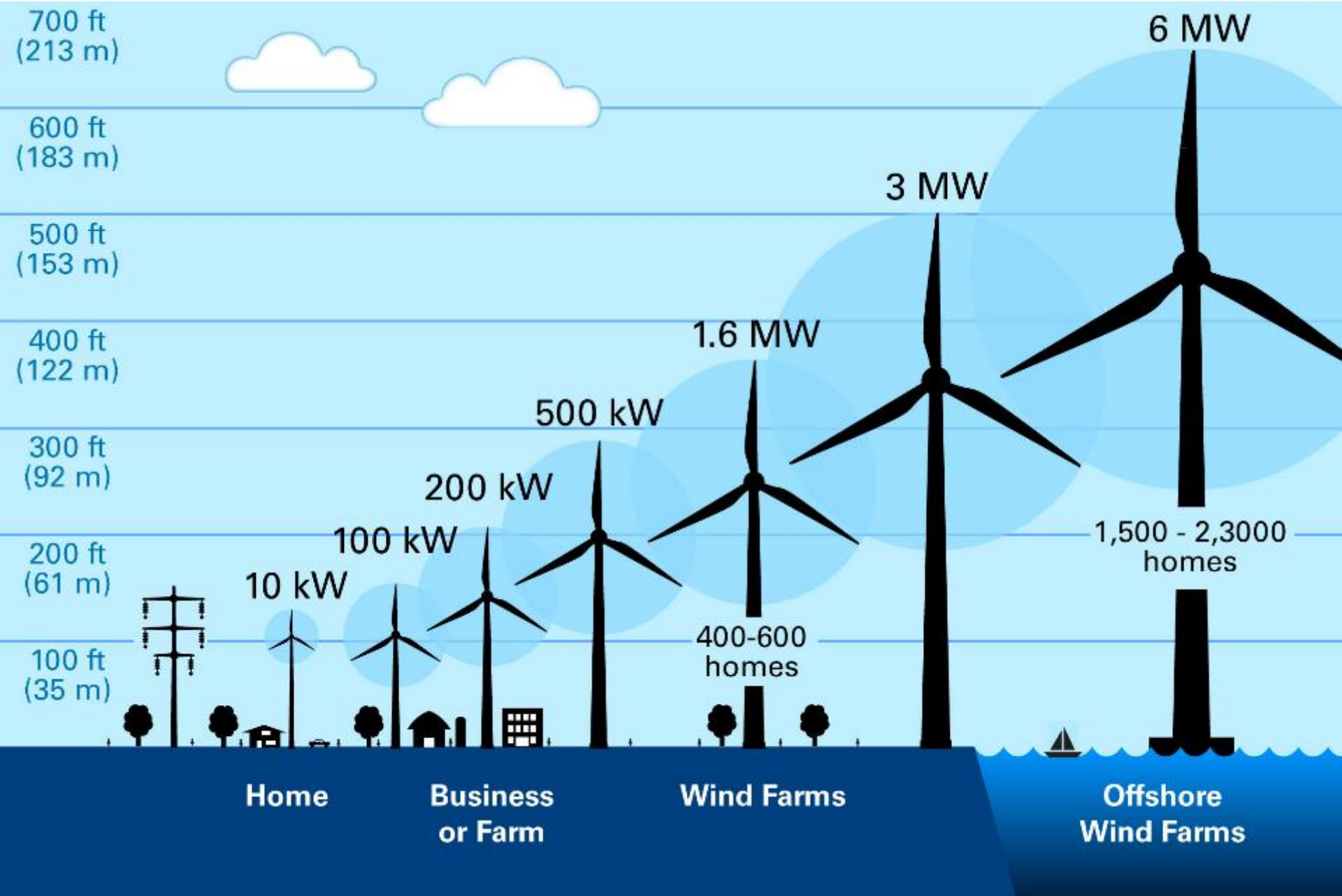
3-bladed horizontal-axis wind turbine (HAWT)



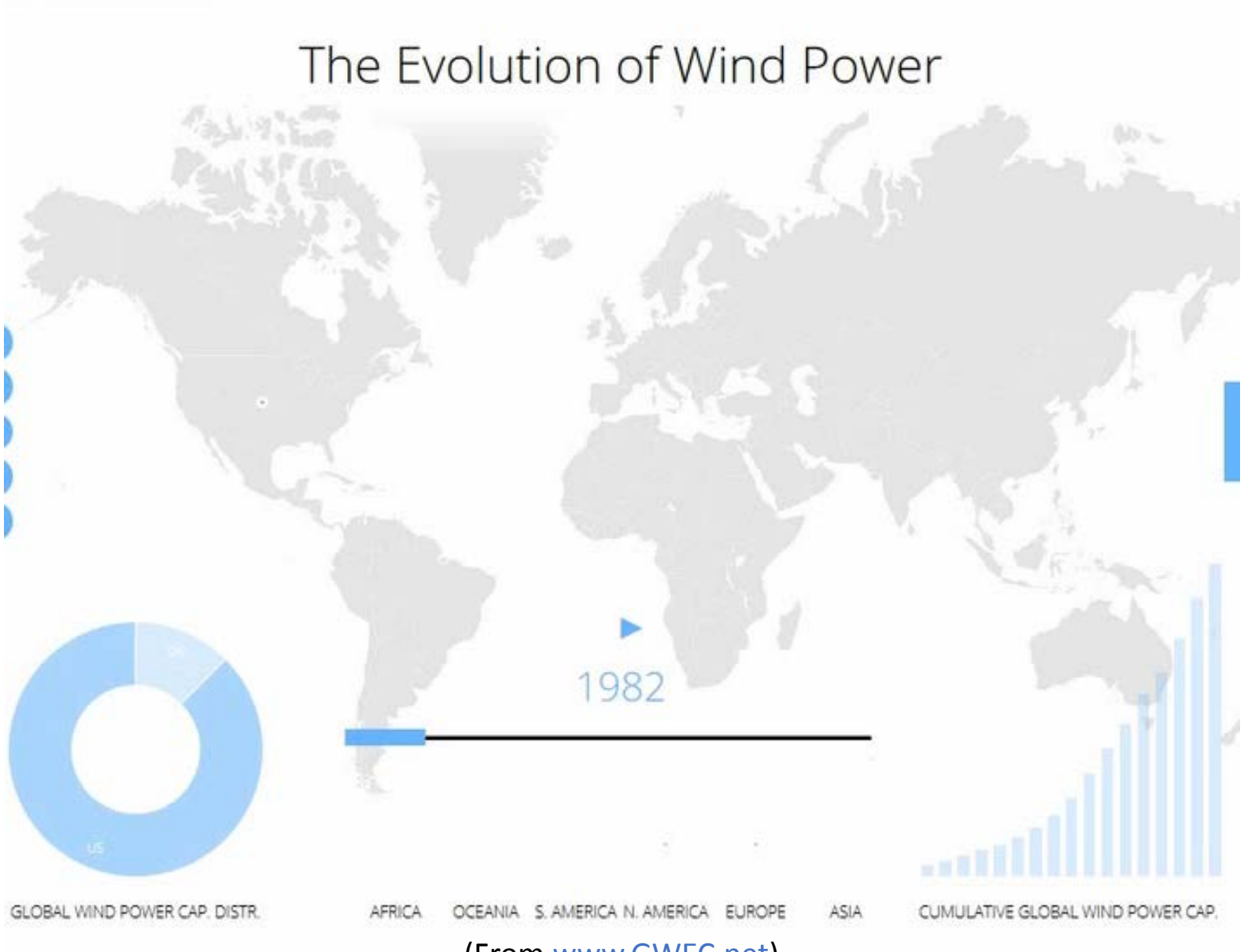
Modern Wind Turbines



Modern Wind Turbines



Recent Evolution



(From www.GWEC.net)

Why Such Growth?

- Clean, zero emissions
  - NOx, SO2, CO, CO2
  - Air quality, water quality
  - Climate change
- Reduce fossil fuel dependence
  - Energy independence
  - Domestic energy—national security
- Renewable
  - No fuel-price volatility
- Distributed power
- Costs are low
  - Increased turbine size
  - R&D advances
  - Manufacturing improvements
- Phase-out of nuclear power

(Partially from The NEED Project)

Potential Impacts and Issues

- Transmission
- Noise
- Visual Impact
- Land Use
- Wildlife Impact

Properly siting a wind turbine can mitigate many of these issues.

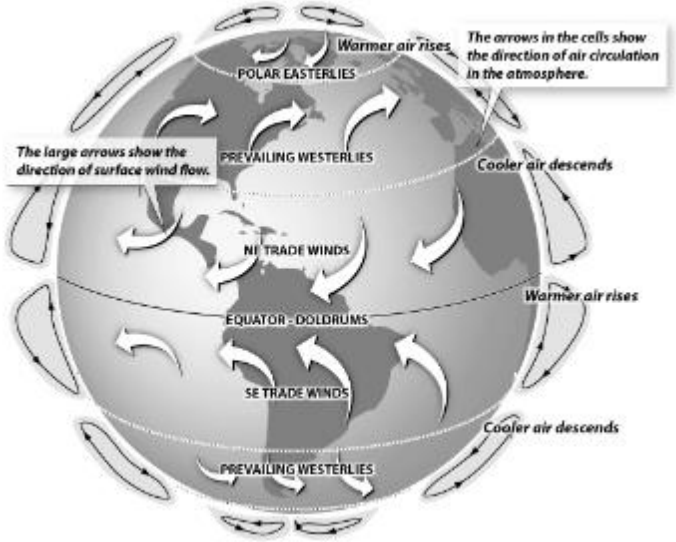
- Uncertainty of Wind

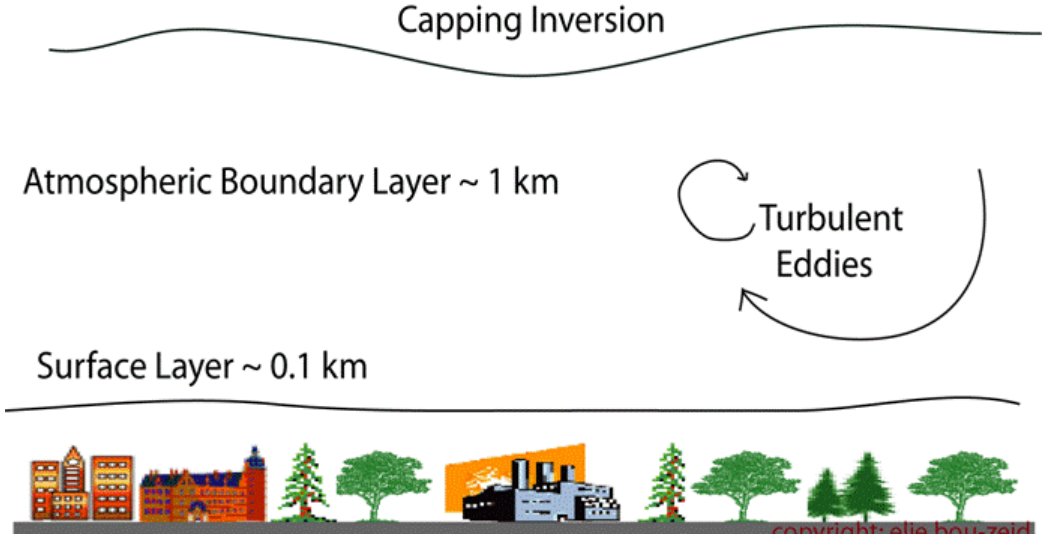
Numerical Simulation of Wind

Macroscale → Mesoscale → Microscale

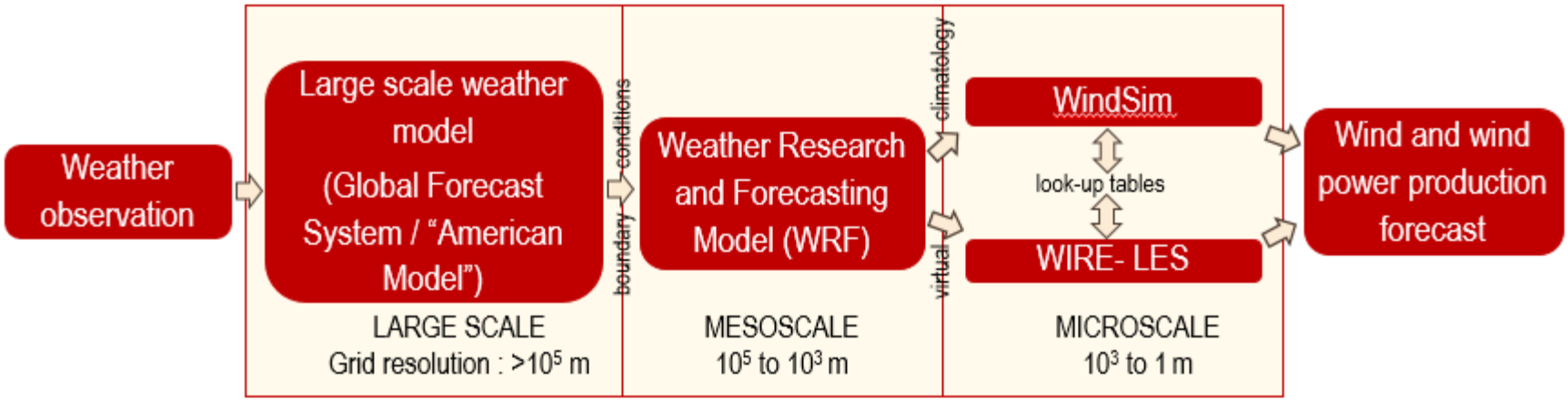


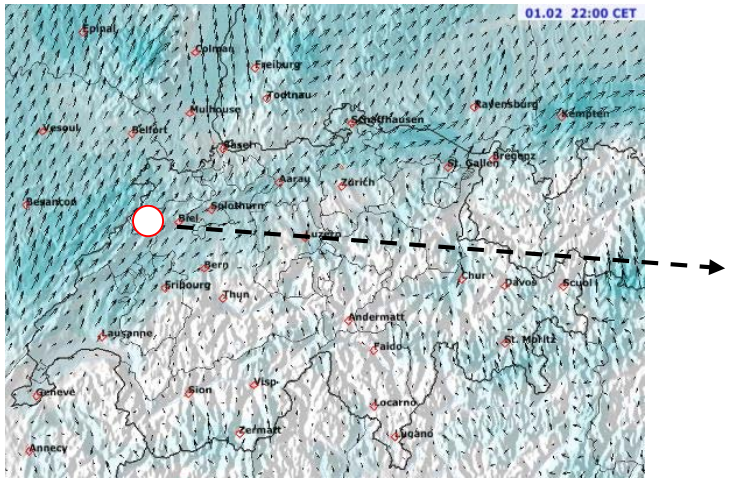


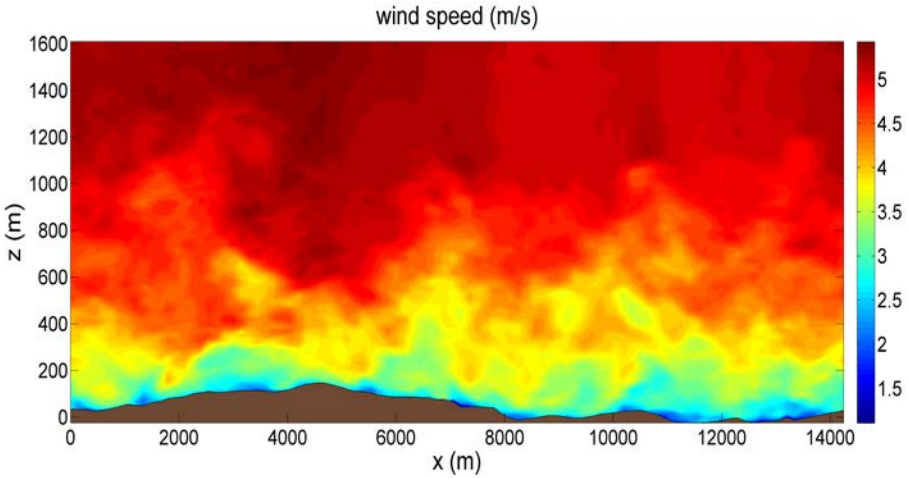





Multi-Scale Modeling Framework





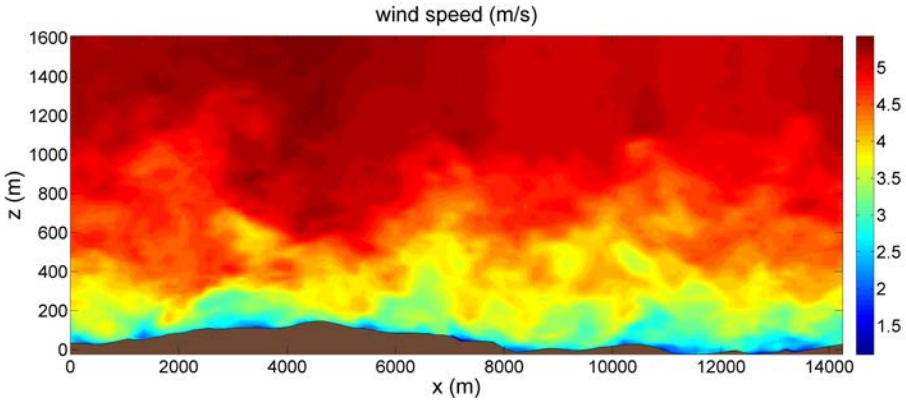


Weather Research and Forecasting (WRF)

Large-Eddy Simulation (LES)

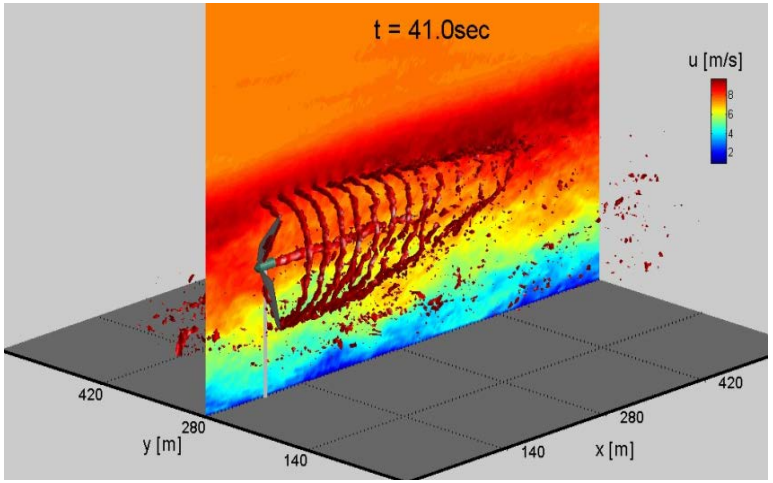
Microscale Model

- **Modeling of turbulent flow in atmospheric boundary layer (ABL)**

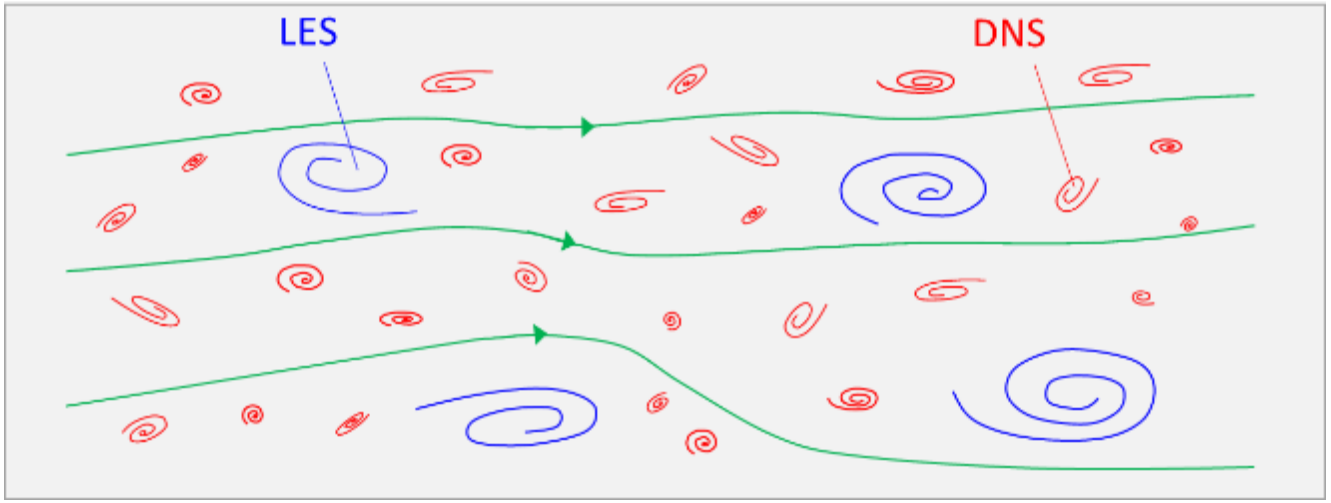


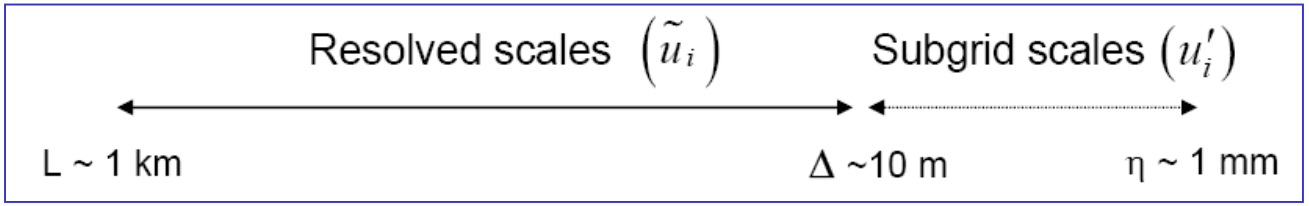
- **Topography representation**

- **Wind turbine modeling**



Large-Eddy Simulation (LES)





$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{\partial \tilde{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \delta_{i3} g \frac{\left(\tilde{\theta} - \left\langle \tilde{\theta} \right\rangle\right)}{\theta_o} + f_c \varepsilon_{ij3} \tilde{u}_j + F_i$$

$$\tau_{ij} = \tilde{u}_i \tilde{u}_j - \widetilde{u_i u_j} \xrightarrow{\textbf{Subgrid Scale (SGS) Model}} \tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t \tilde{S}_{ij}$$

SGS Model

Lagrangian Averaged Scale-Dependent Dynamic Model

Stoll, R., and Porté-Agel, F. (2006). WATER RESOURCES RESEARCH, 42(1), W01409.

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2[\Delta C_s(t, \boldsymbol{r}, \Delta)]^2 \left|\tilde{\boldsymbol{S}}\right| \tilde{S}_{ij}$$

Dynamic Computation | Two equations for C_s and β

$$C_s^2 = \frac{\langle L_{ij} M_{ij} \rangle}{\langle M_{ij} M_{ij} \rangle} \qquad C_s^2 = \frac{\langle Q_{ij} N_{ij} \rangle}{\langle N_{ij} N_{ij} \rangle}$$

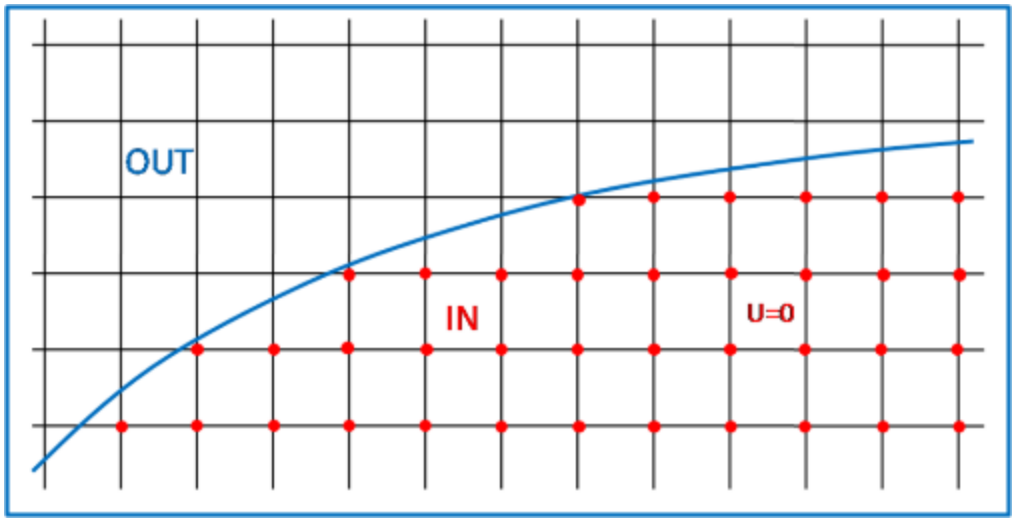
$$L_{ij} = \overline{\tilde{u}_i \tilde{u}_j} - \overline{\tilde{u}}_i \overline{\tilde{u}}_j, \qquad M_{ij} = 2\Delta^2 \left(|\overline{\widetilde{\mathcal{S}}}| \overline{\widetilde{S}}_{ij} - \alpha^2 \beta |\overline{\widetilde{\mathcal{S}}}| \overline{\widetilde{S}}_{ij} \right)$$

$$Q_{ij} = \widehat{\tilde{u}_i \tilde{u}_j} - \hat{\tilde{u}}_i \hat{\tilde{u}}_j, \qquad N_{ij} = 2\Delta^2 \left(|\widehat{\widetilde{\mathcal{S}}}| \widehat{\widetilde{S}}_{ij} - \alpha^4 \beta^2 |\widehat{\widetilde{\mathcal{S}}}| \widehat{\widetilde{S}}_{ij} \right)$$

- **Major advantages:**
  - **Turbulence resolving** (➔ **less uncertainty!**)
  - **No tuning** of coefficients is required.
  - **Accurate**, based on validation tests.

Topography Representation

Immersed boundary method (IBM)



$$\tau_w = -\rho \left[\frac{\kappa |\mathbf{v}_t|}{\ln(1+\delta/z_0)} \right]^2,$$

$$u_i^* = u_i^n + \frac{3}{2}\Delta t R_i^n - \frac{1}{2}\Delta t \left[R_i^{n-1} - \frac{\partial p^{n-1}}{\partial x_i} \right],$$

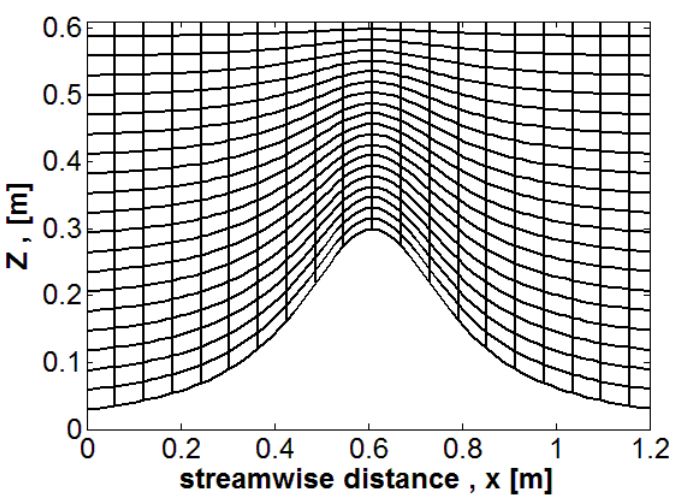
$$\frac{\partial^2 p^n}{\partial x_i \partial x_i} = \frac{2}{3\Delta t}\frac{\partial u_i^*}{\partial x_i} + \frac{2}{3}\frac{\partial f_i^n}{\partial x_i}.$$

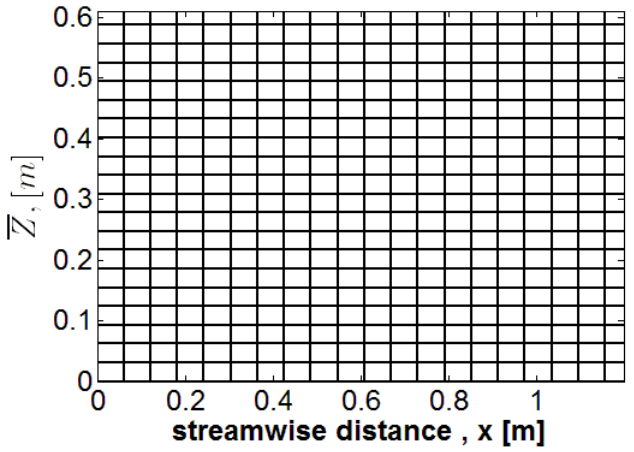
$$u_i^{n+1} = u_i^* - \frac{3}{2}\Delta t \frac{\partial p^n}{\partial x_i} + \Delta t f_i^n,$$

$$f_i^n(\boldsymbol{x}) = \begin{cases} (3/2)(\partial p^n/\partial x_i) - (u_i^* - u_i^{\text{desired}})/\Delta t & \text{if } \varphi(\boldsymbol{x}) \leqslant 0, \\ 0 & \text{if } \varphi(\boldsymbol{x}) > 0. \end{cases}$$

Topography Representation

Terrain Following Coordinate Transformation



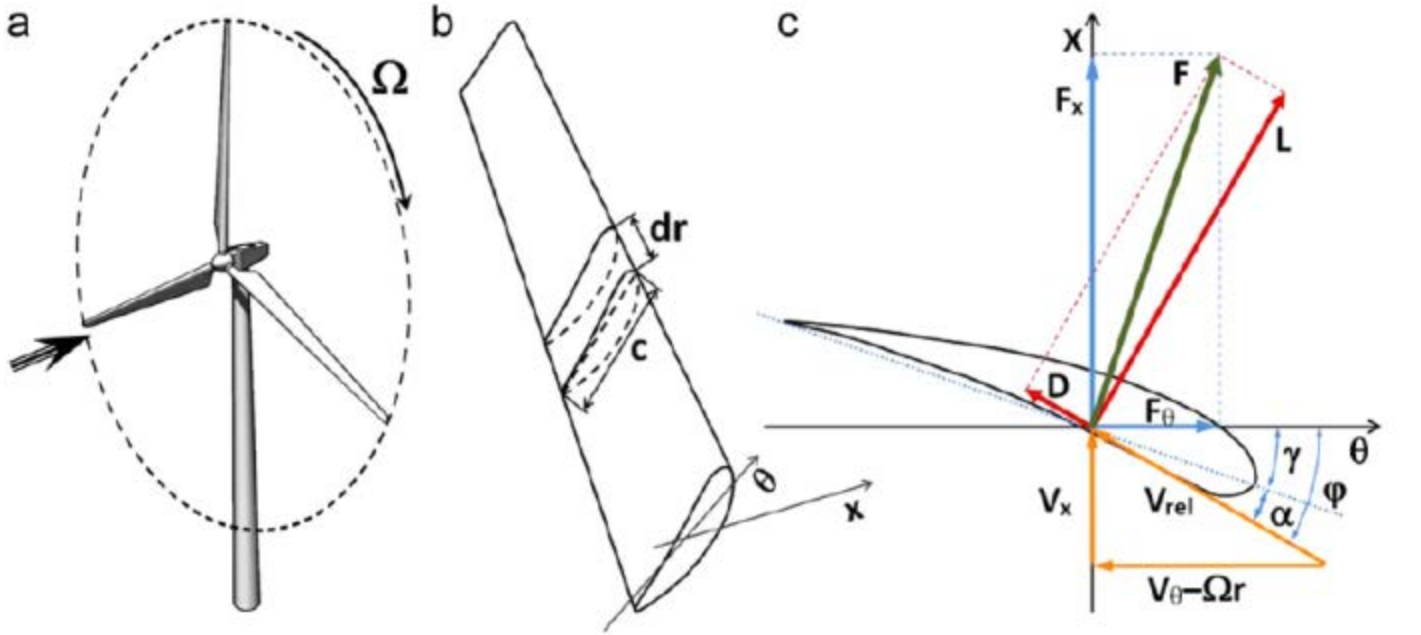


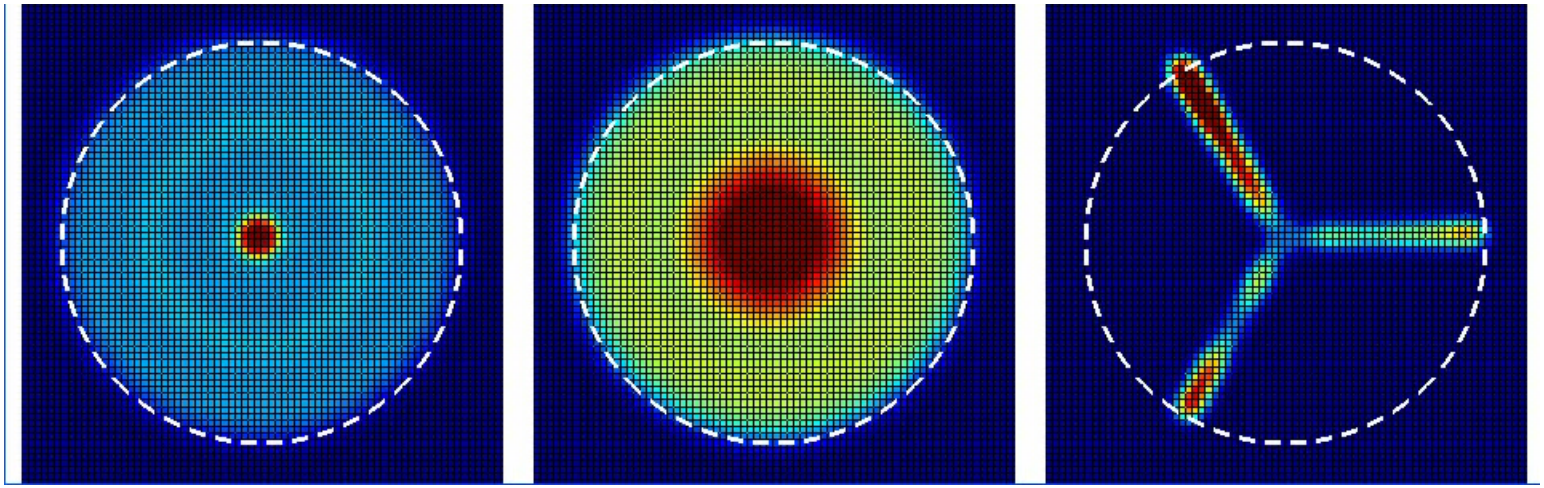
$$\bar{z} = H\frac{z - z_s}{H - z_s} \qquad \bar{x} = x \qquad \bar{y} = y$$

H : *Maximum Height of the domain*

$Z_s(x, y)$: *Surface equation of the topography*

Wind Turbine Modeling

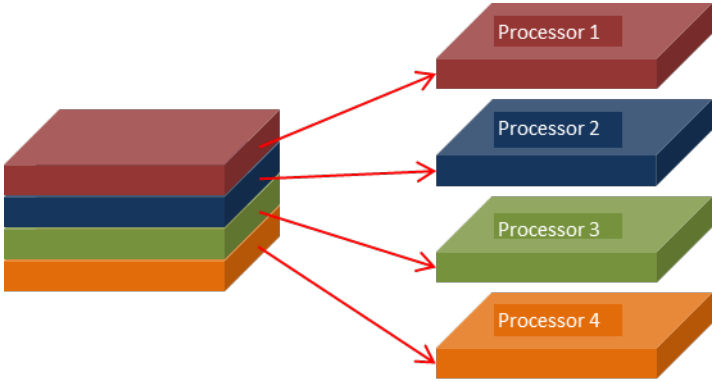




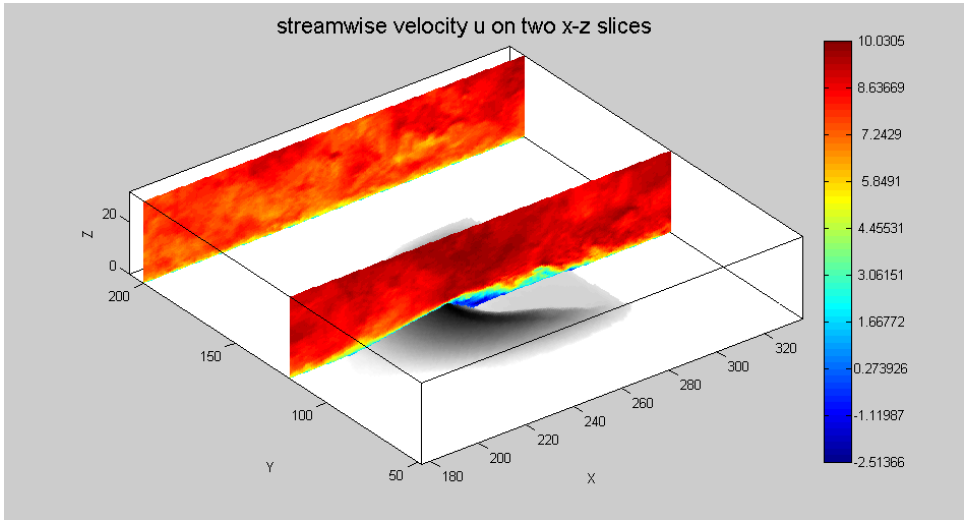
Actuator-disk model **Actuator-disk model with rotation** **Actuator-line model**

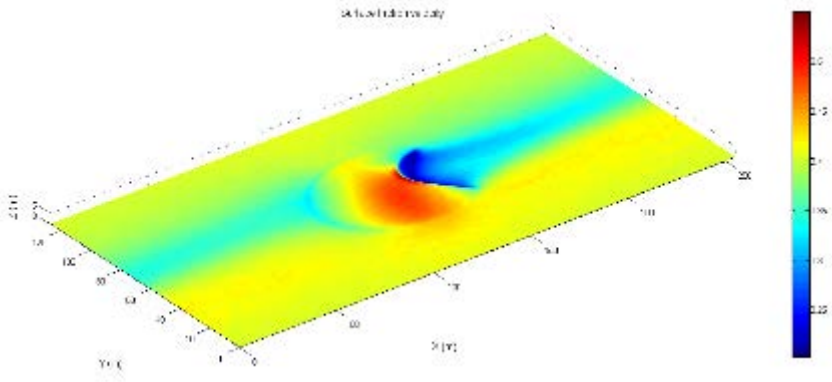
WIRE-LES Code

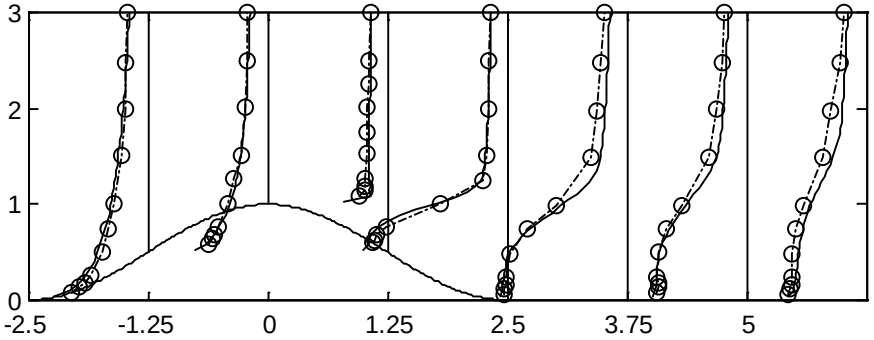
- Spectral method combined with FDM
- Adams-Bashforth scheme in time
- Direct solver for the Poisson's equation for pressure
- Parallelized using hybrid MPI/OpenMP
- Various SGS models (e.g., scale-dependent Lagrangian dynamic model)
- Immersed boundary method
- Terrain-Following Coordinate Transformation



Validation Tests

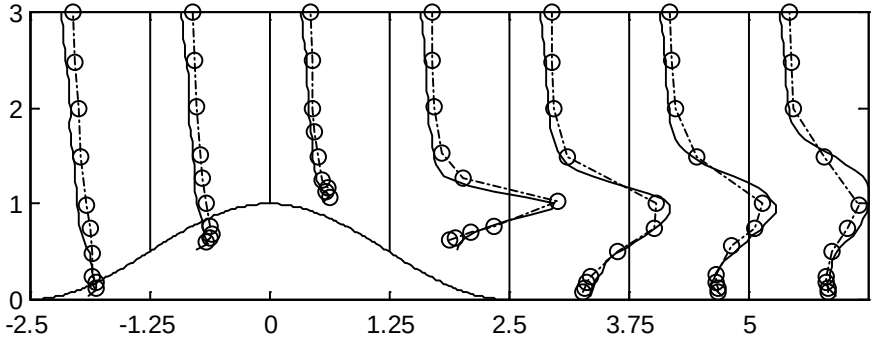






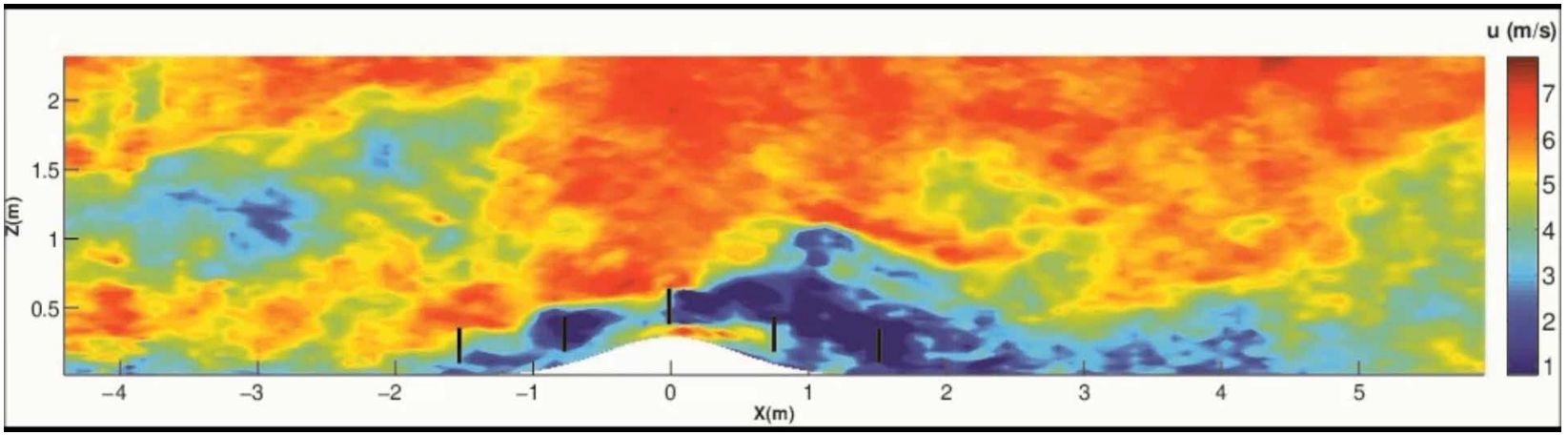
U/U_h

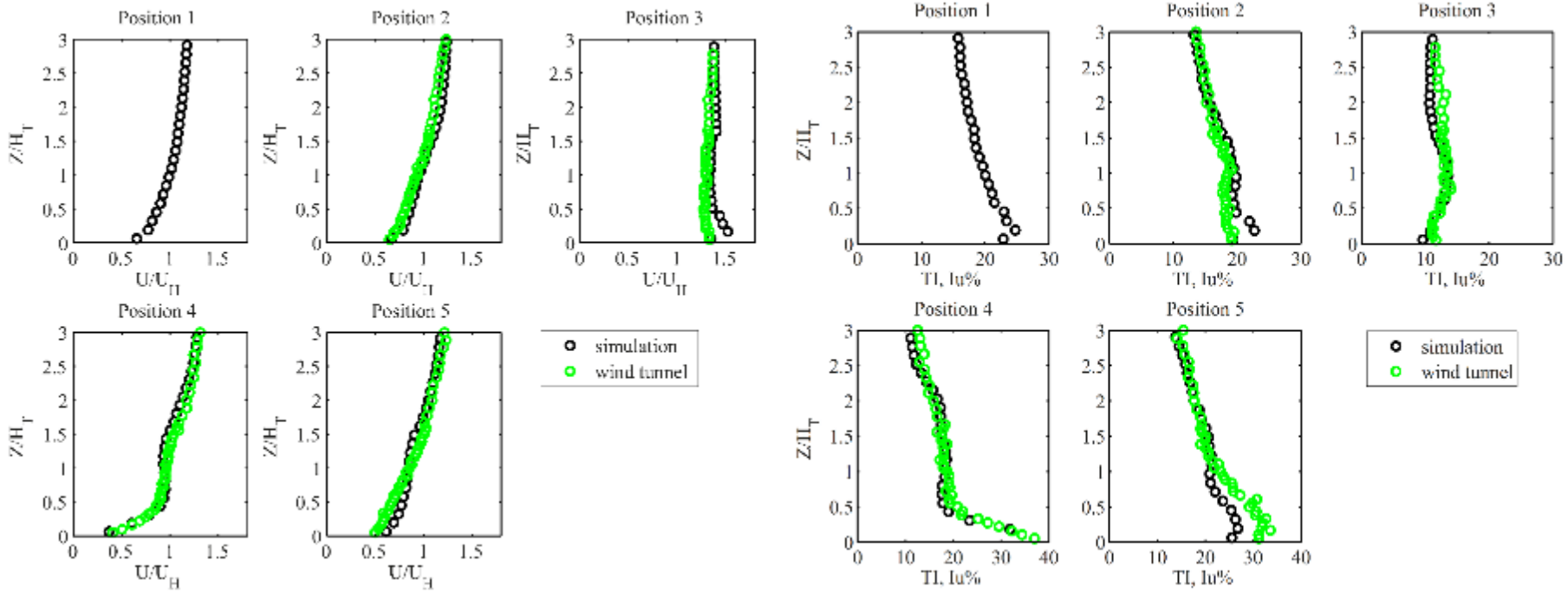
circle – experiment
line – simulation



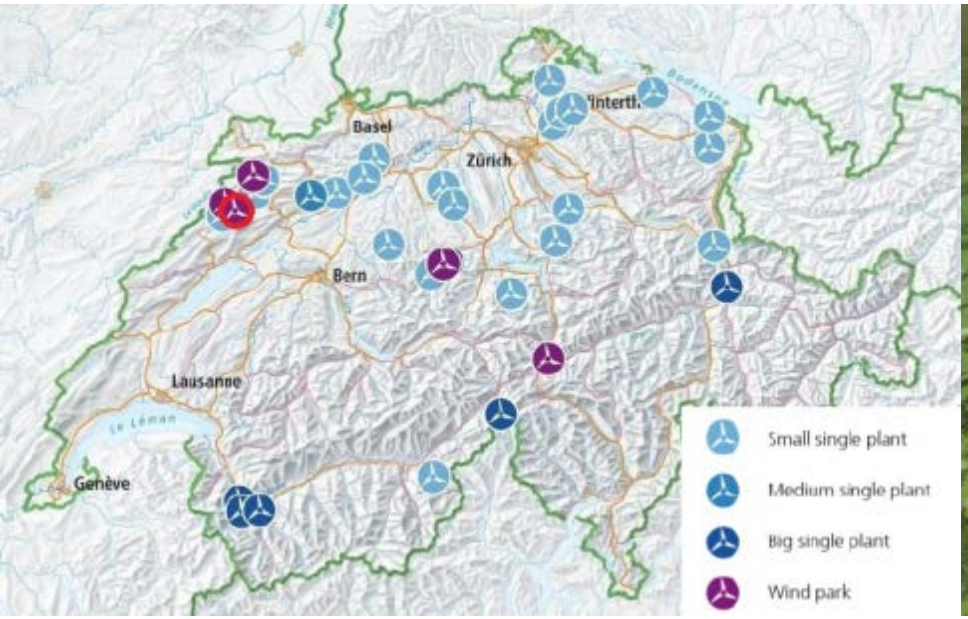
σ_U/U_h

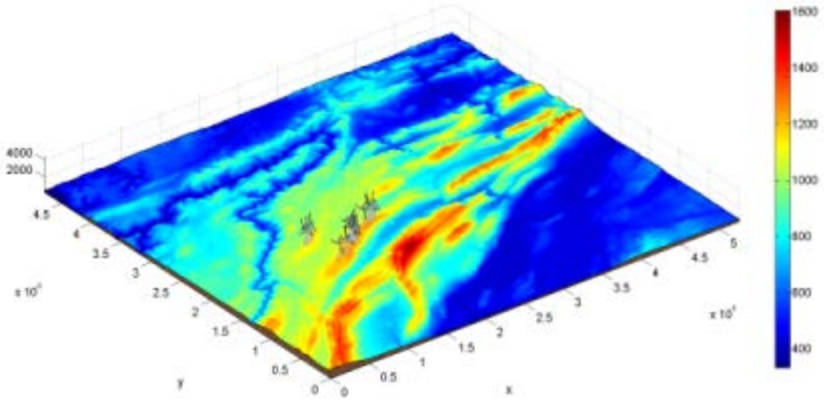
Validation Tests

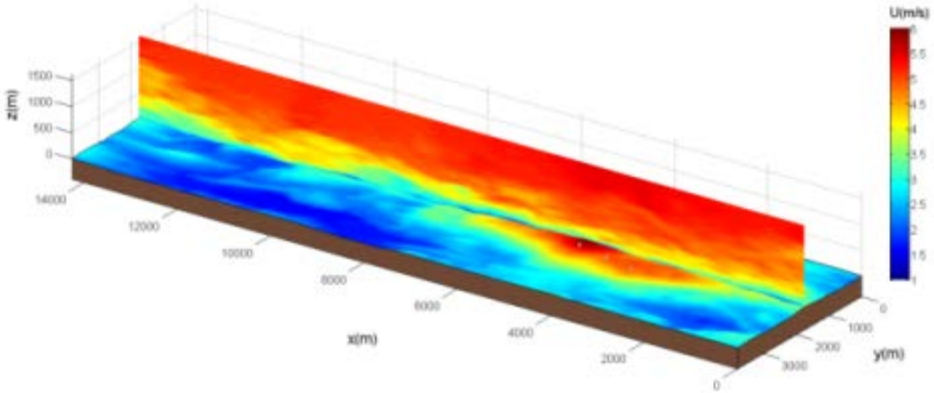




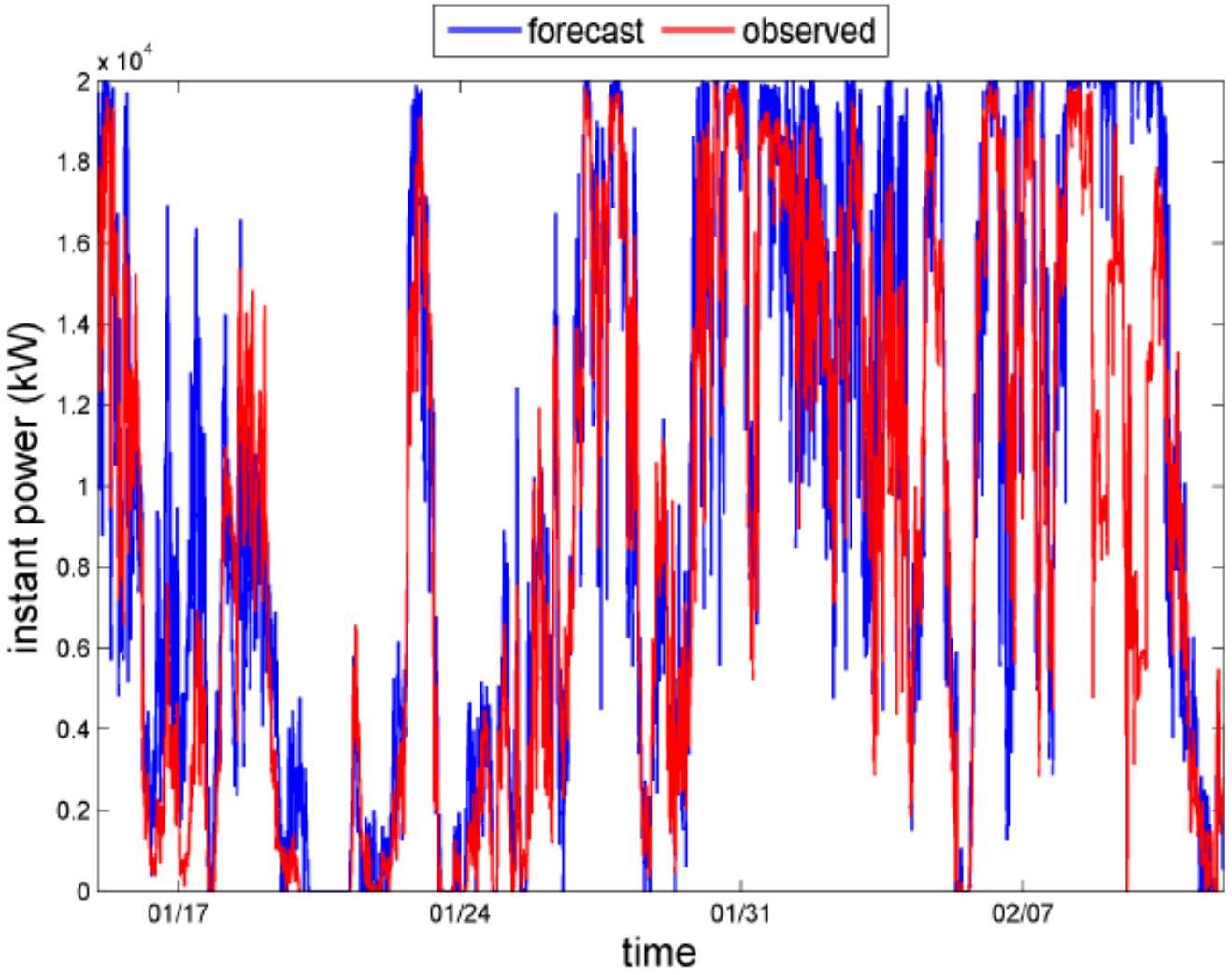
Case Study: Juvent Wind Farm







Case Study: Juvent Wind Farm



Comparison between observed and simulated total power for the idealized case

Future Works

- Continuing the development of the coupling technique
- Reducing the errors in the mesoscale simulations
- Improving the performance of the microscale models for complex terrain
- Performing further validation of the coupled model against more field data
- Developing and testing wind-farm control strategies based on the simulation data
- Applying the developed tools to study selected cases most relevant to the Swiss Energy 2050 strategies

SCCER - FURIES

ANNUAL CONFERENCE 2017

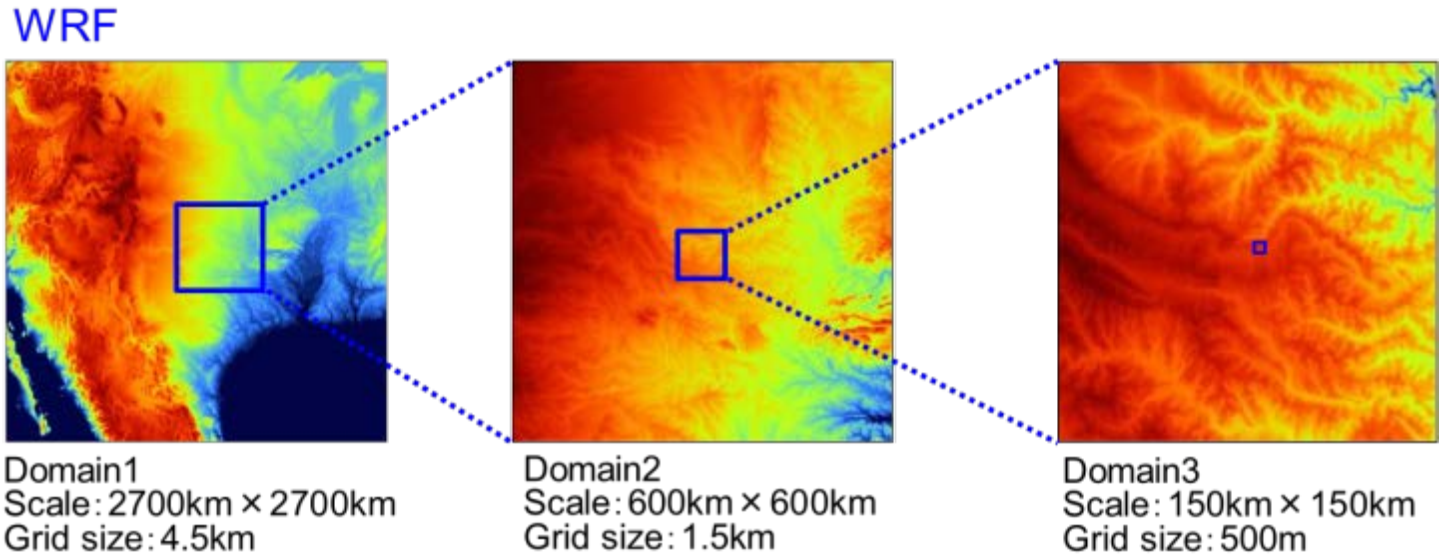
Swiss Tech Convention Center - EPFL - Lausanne - November 2nd

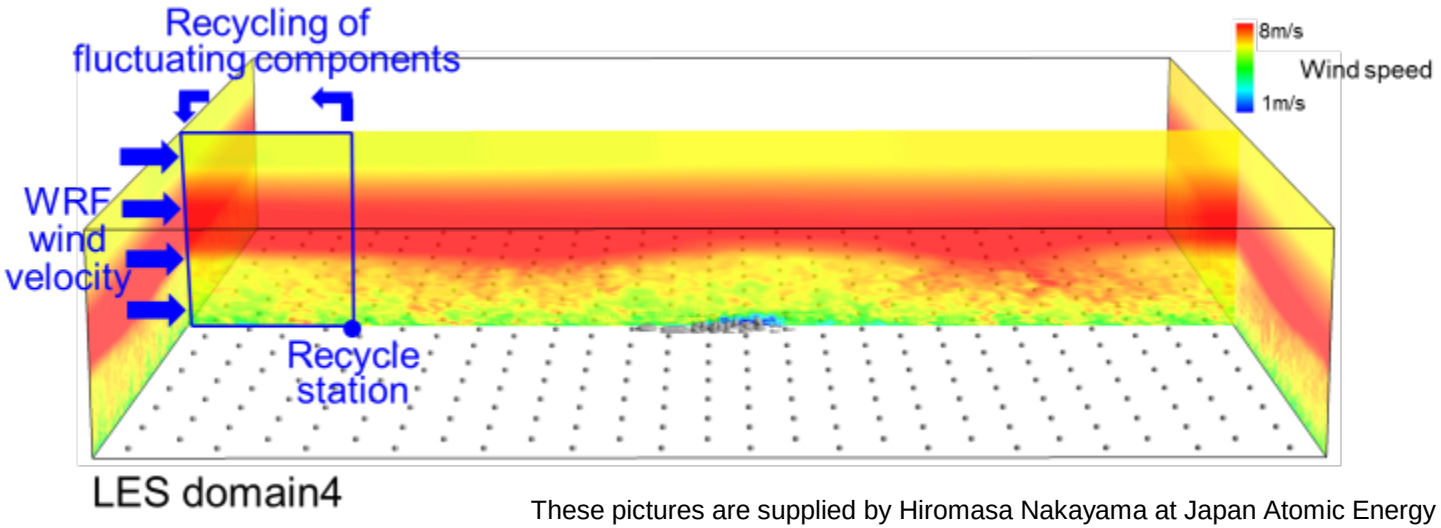
Thanks for your attention !

QUESTIONS or FOODS?

Multi-Scale Modeling

Strategies of **multi-scale modeling** through an optimal coupling of our **LES** code with the mesoscale weather modeling code **WRF** are being evaluated.





These pictures are supplied by Hiromasa Nakayama at Japan Atomic Energy Agency