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BEAM-ME

Application and performance evaluation of a parallel solver for energy system models with high spatial and temporal resolution

EURO 2019, Dublin, June 25th 2019

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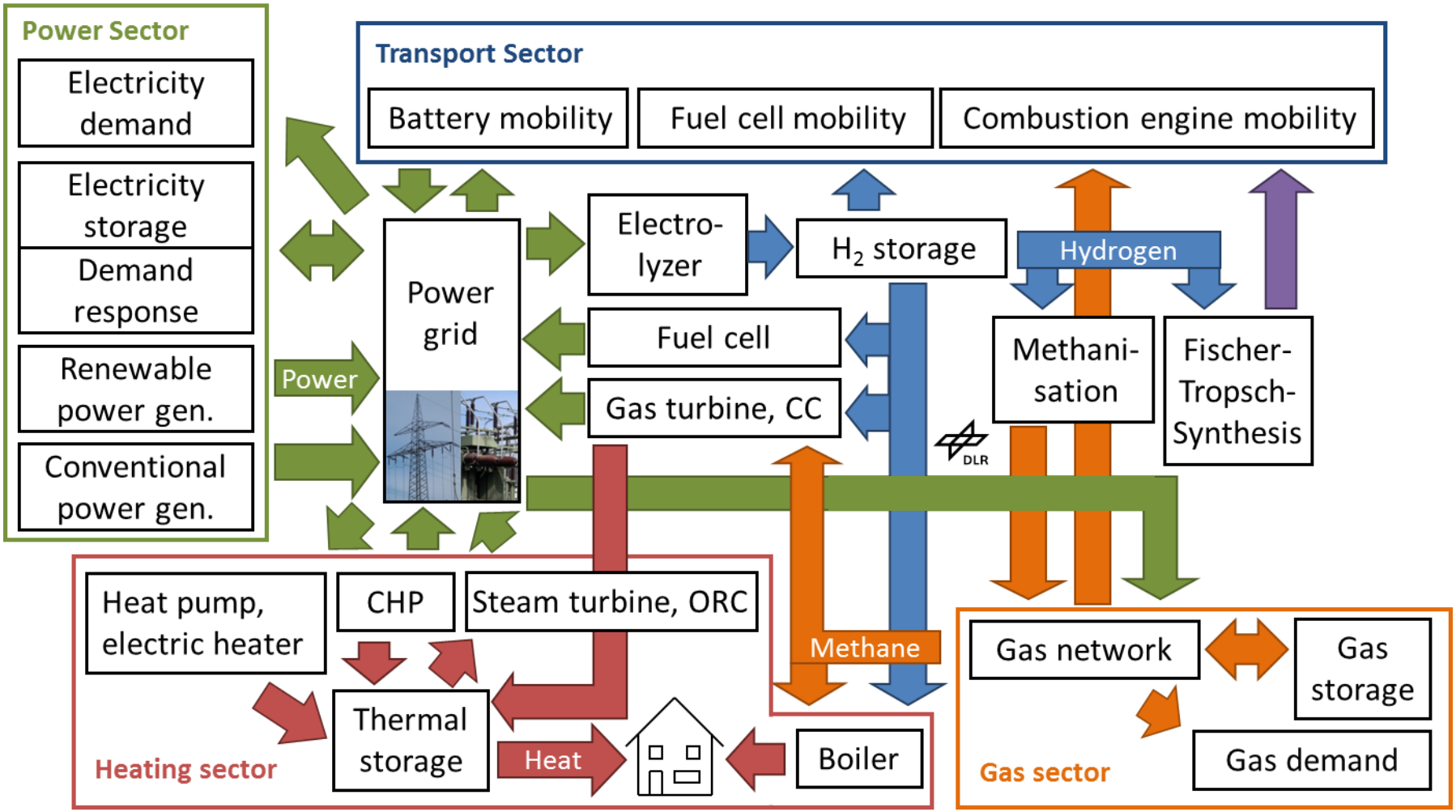
Energy Systems Analysis

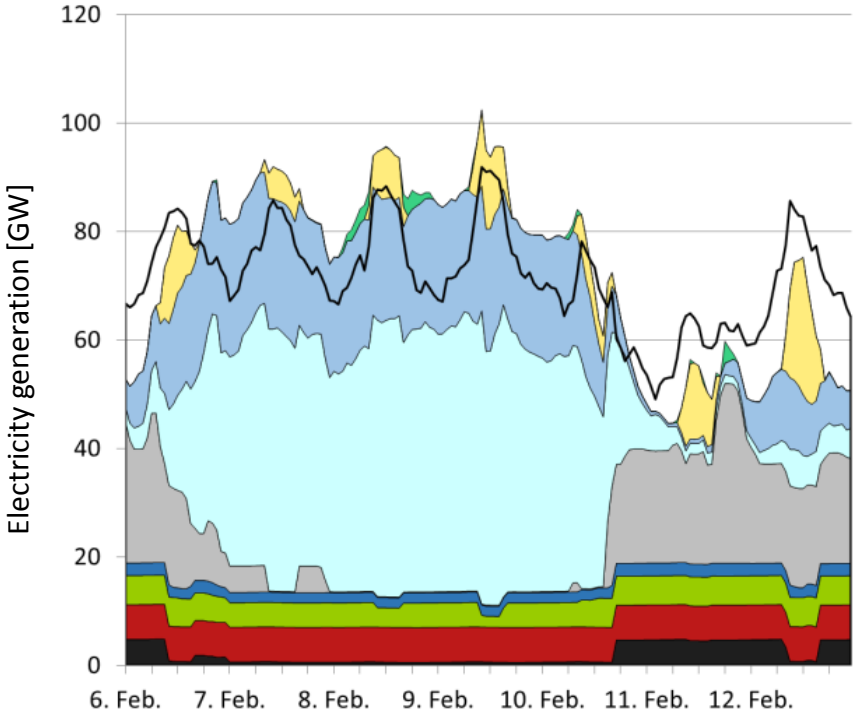
HLRS · berlin · GAMS · JÜLICH Forschungszentrum · DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center · ZIB

Increasing energy system complexity



Dimensionality of REMix problems

60 geographical regions,
86 AC transmission lines,
128 HVDC transmission lines

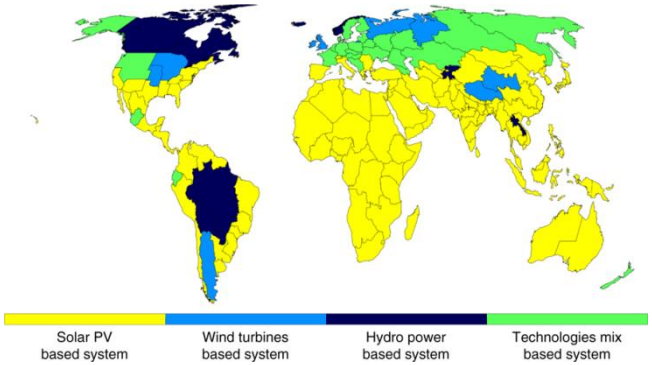


~ 30 technologies
8760 time steps per year

System cost minimization problems with up to 120 mio. variables and constraints

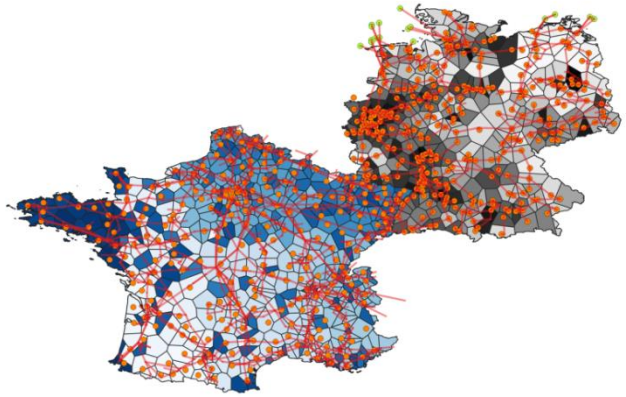
Trends in energy system models

Focus on global energy systems



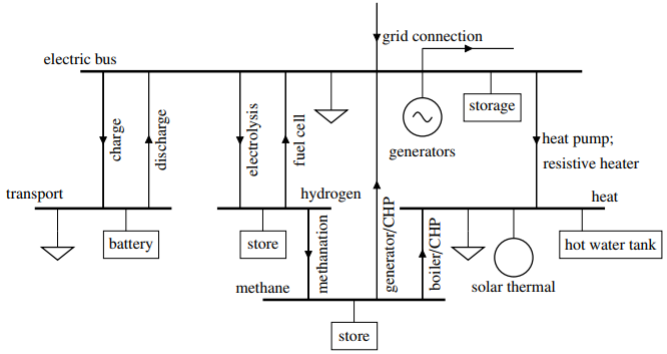
Bogdanov et al., 2019, Radical transformation pathway towards sustainable electricity via evolutionary steps

Higher spatial resolution



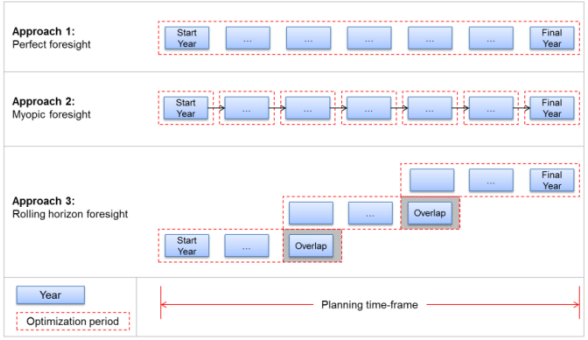
Current work-in-progress from Cao et al.

Sector integration studies



Brown et al., 2018, Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system

Transformation pathways

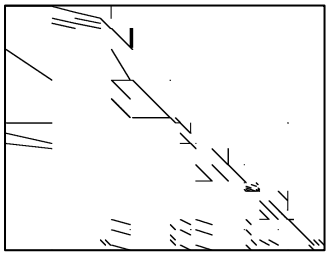


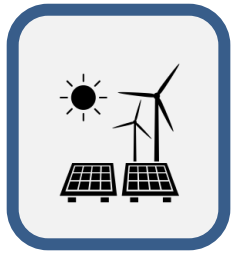
Fichter, 2018, Long-term Capacity Expansion Planning with Variable Renewable Energies

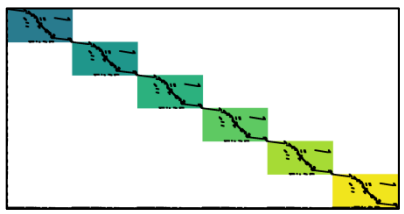
Solving energy system models

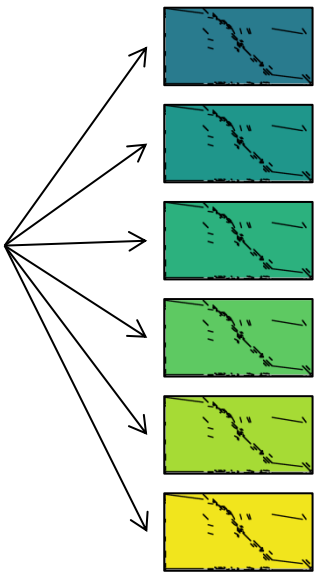
math. formulation **solver call** **optimization results**

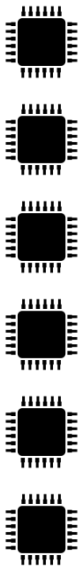
$$\min c \cdot x$$
$$A \cdot x \leq b$$

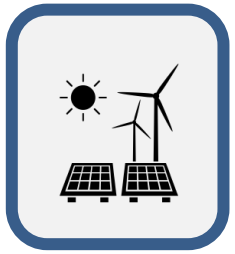








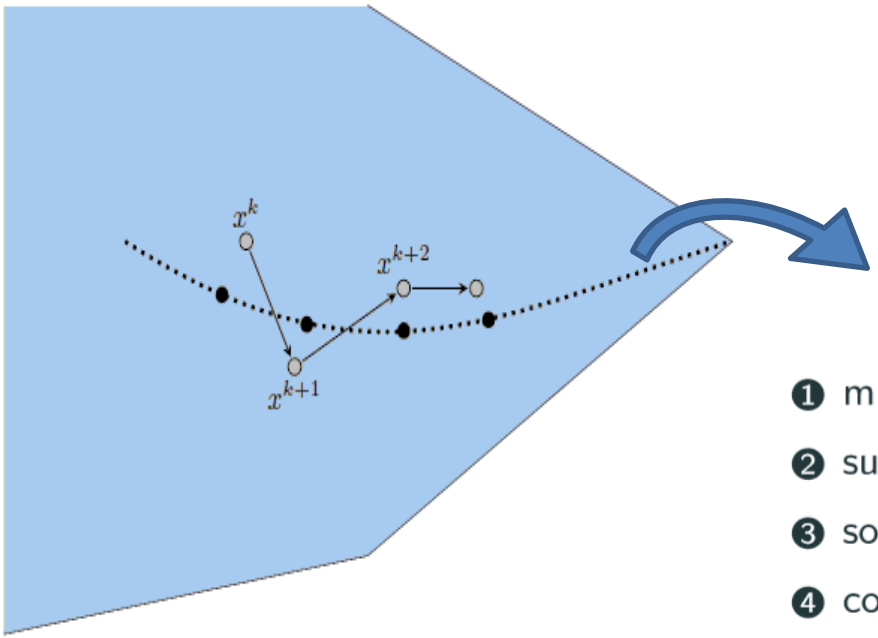




block structure **split and distribute** **parallel solve** **merge** **optimization results**

The PIPS-IPM solver

Solution approach in a nutshell:
Each step of an interior-point algorithm requires solution of a linear system
This can be parallelized by exploiting a block diagonal structure



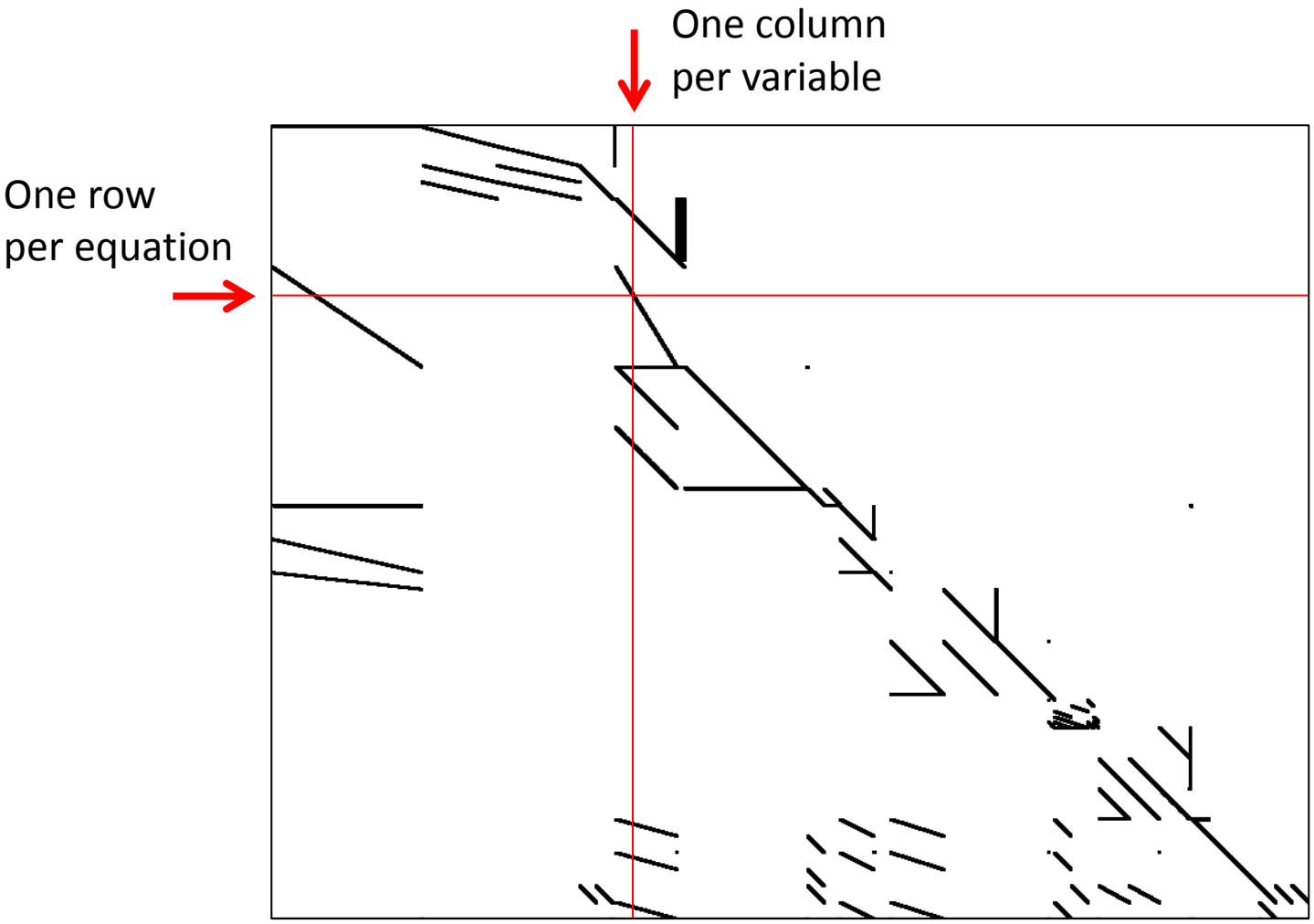
$$\begin{bmatrix} K_1 & & & B_1 \\ & \ddots & & \vdots \\ & & K_N & B_N \\ B_1^T & \cdots & B_N^T & K_0 \end{bmatrix} \begin{bmatrix} \Delta z_1 \\ \vdots \\ \Delta z_N \\ \Delta z_0 \end{bmatrix} = \begin{bmatrix} r_1 \\ \vdots \\ r_N \\ r_0 \end{bmatrix}$$

1. multiply rows $i = 1, \ldots, N$ by $-B_i^T K_i^{-1}$.
2. sum up all rows
3. solve $\left(K_0 - \sum_{i=1}^{N} B_i^T K_i^{-1} B_i\right) \Delta z_0 = r_0 - \sum_{i=1}^{N} B_i^T K_i^{-1} r_i$.
4. compute $\Delta z_i, i = 1, \ldots, N$.

D. Rehfeldt, The newly developed PIPS solver, May 24th 2019, BEAM-ME Workshop, Aachen

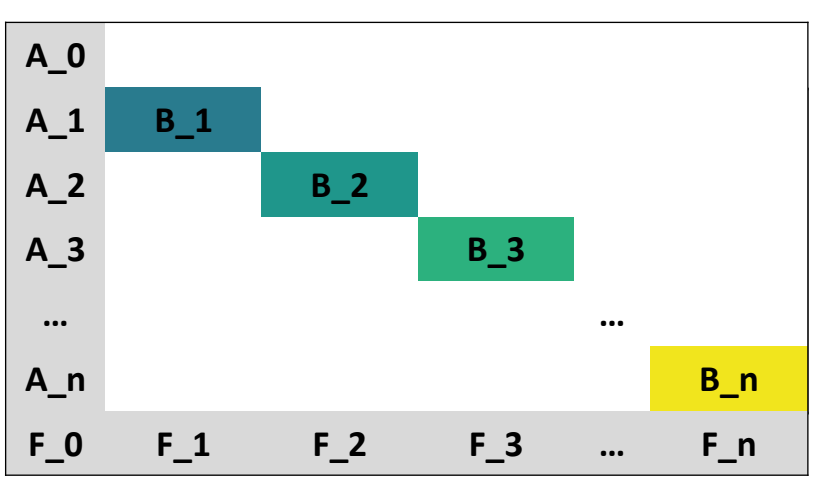
PIPS-IPM requires a block diagonal structure to solve problems in parallel

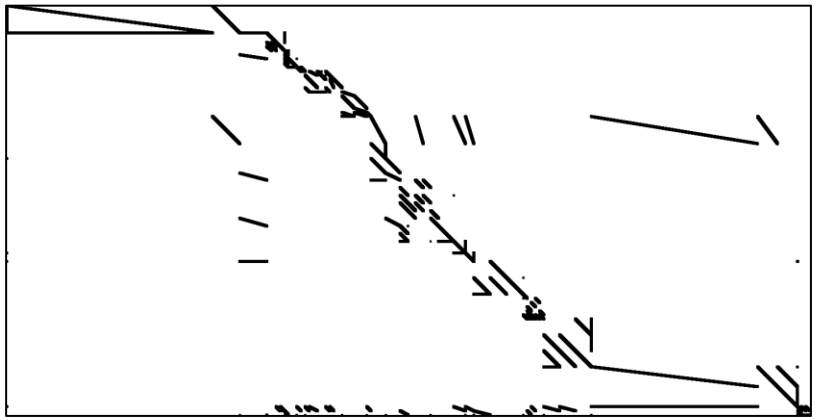
The optimization matrix

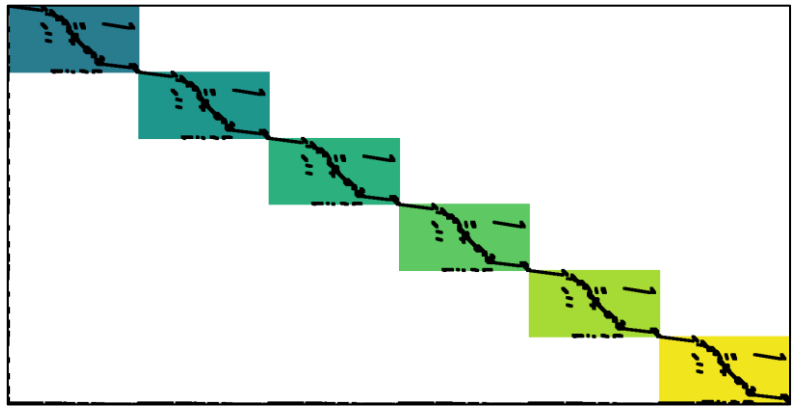


Rows and columns can be permuted without changing the optimization problem

From ESM to PIPS: Annotation

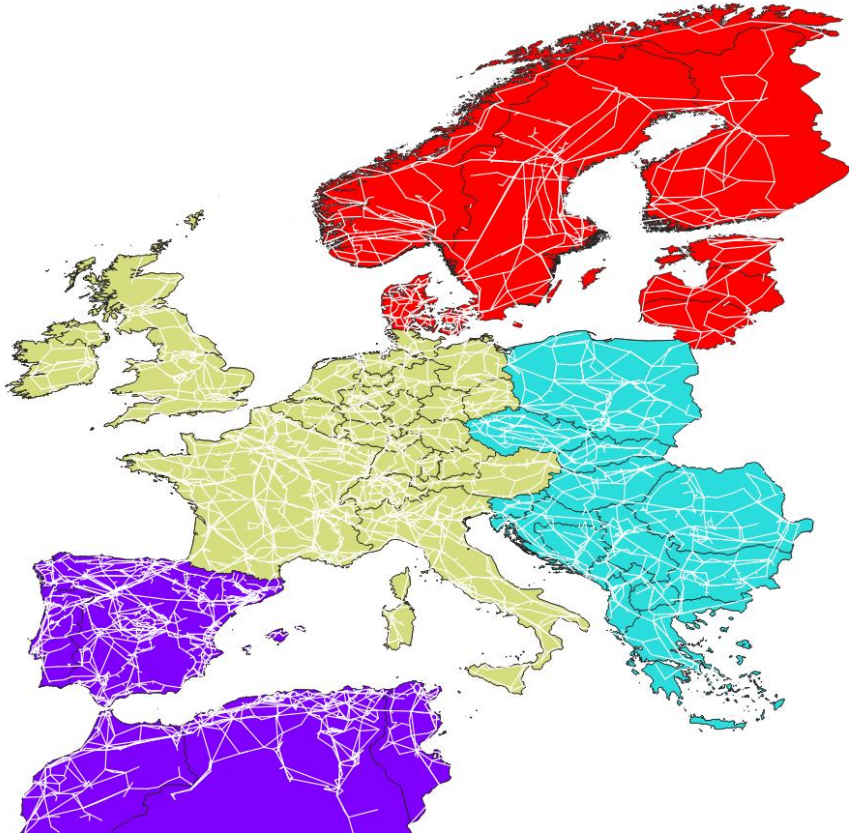


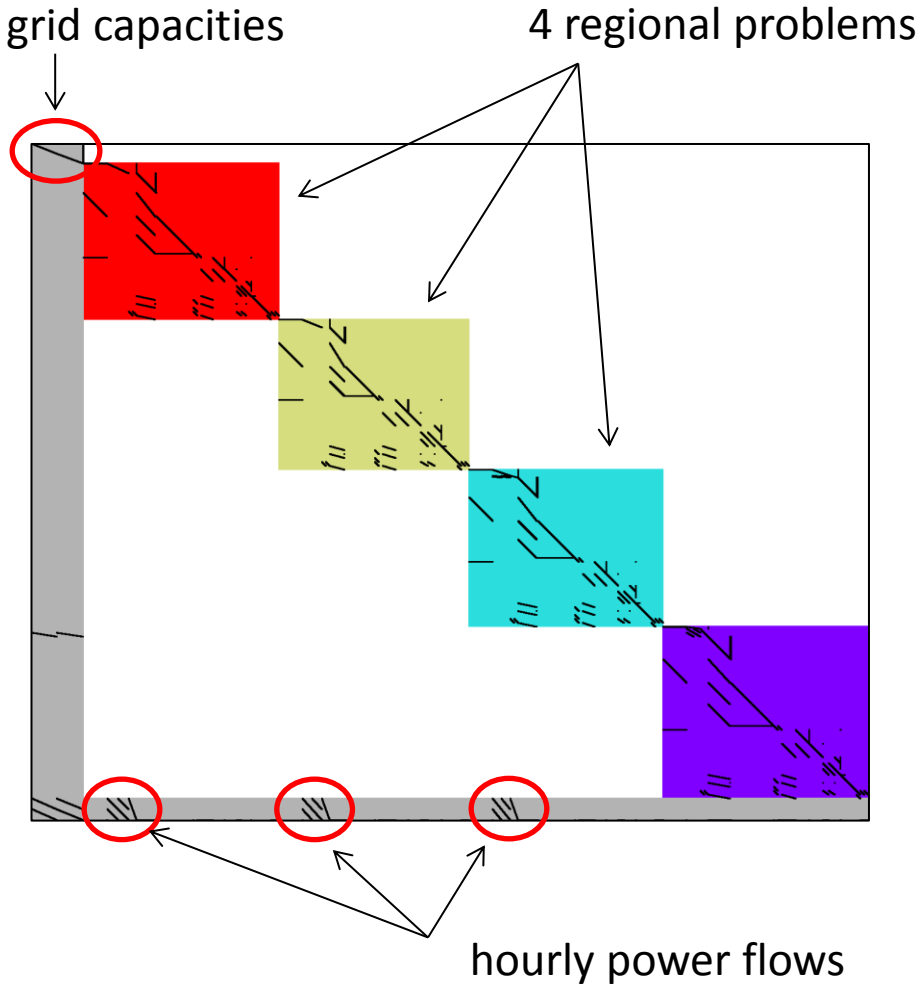




Annotation pre-structures the optimization problem for PIPS-IPM

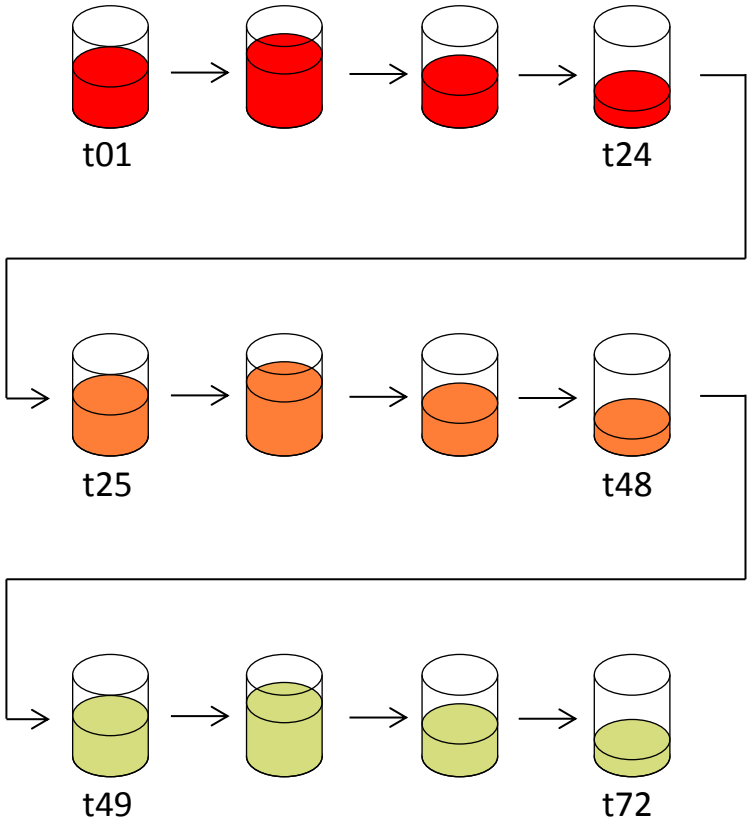
Spatial decomposition

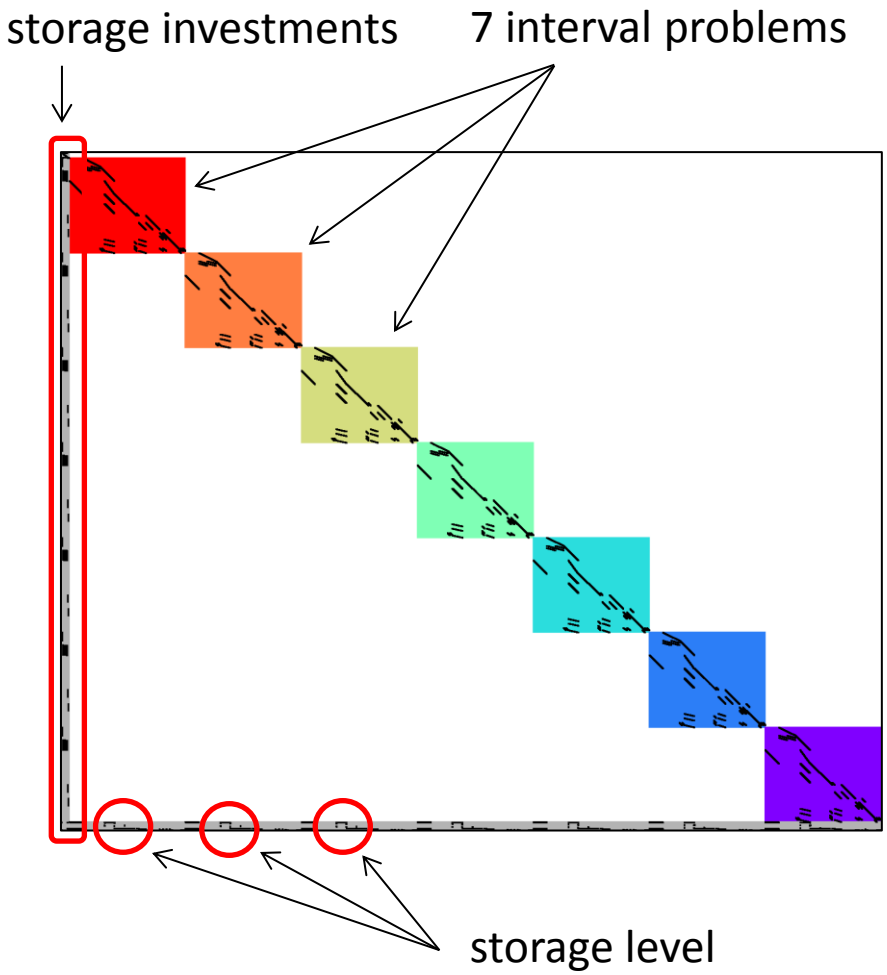




Linking elements scale with transmission lines and time steps

Temporal decomposition



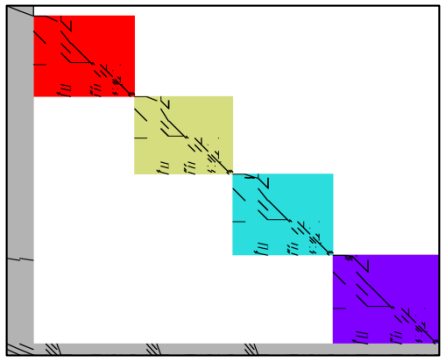


Linking elements scale with regions and technologies

Annotation variations in REMix

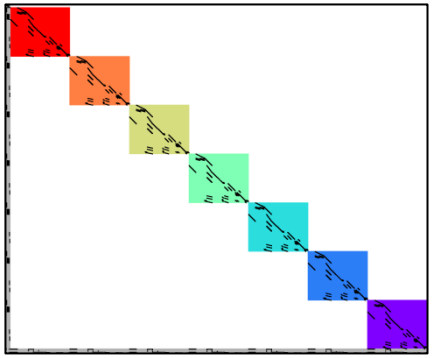
BEAM-ME

Regional decomposition



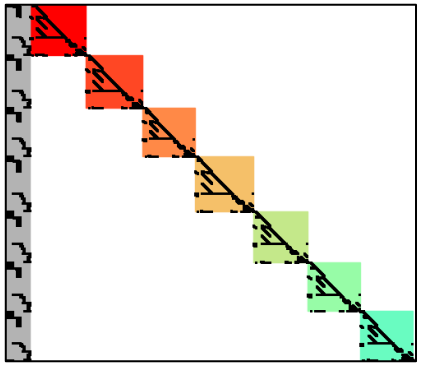
Large number of linking elements

Temporal decomposition



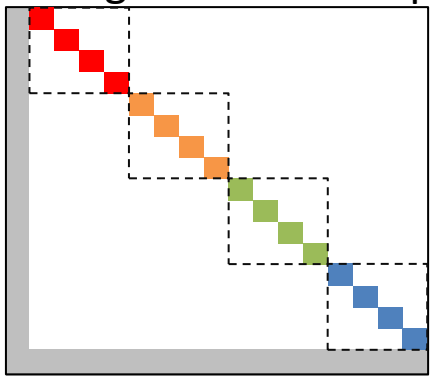
Most promising with up to 8760 blocks

Planning horizon decomposition



Limited number of blocks

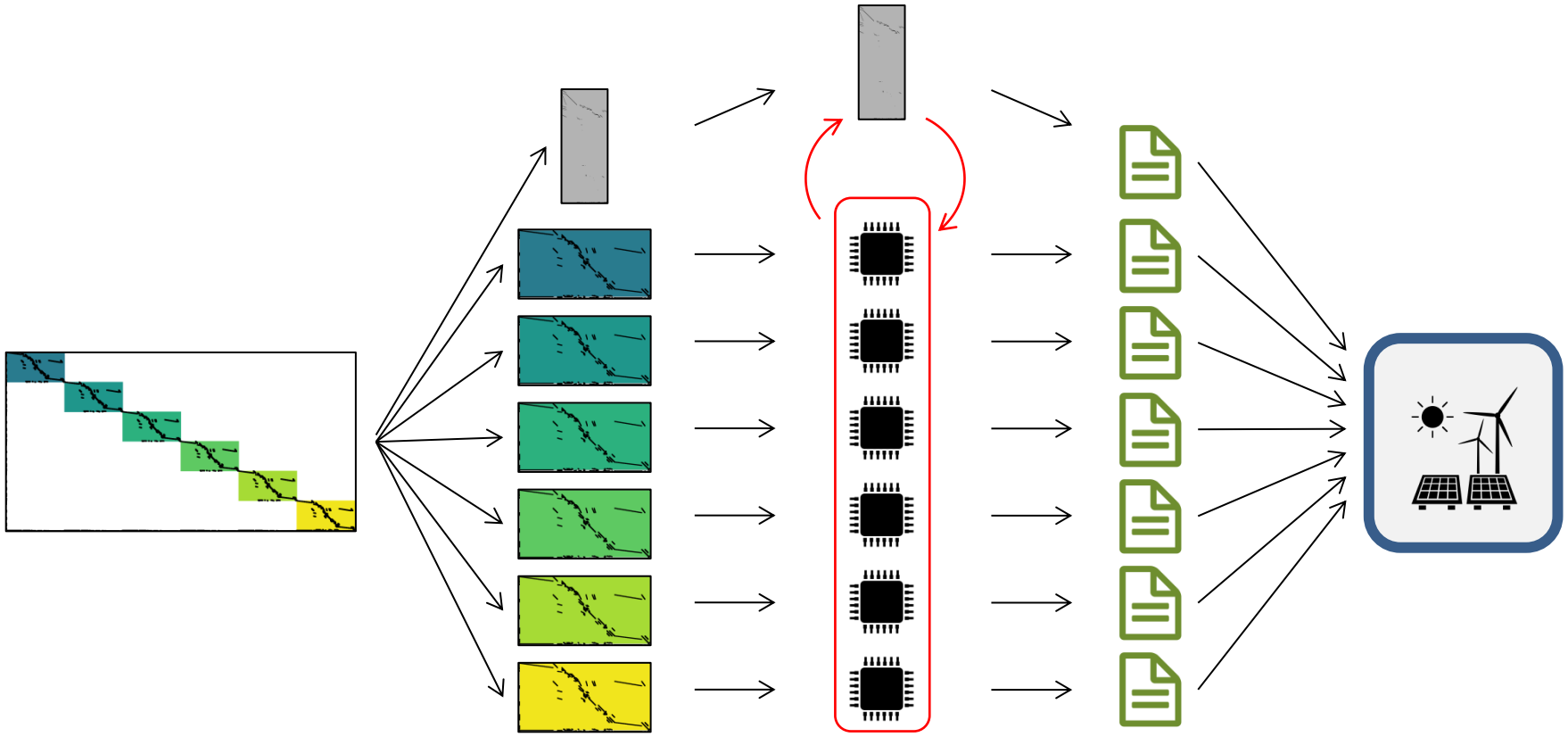
Planning horizon + temporal decomp.



High synergies between annotation variations

Different annotations result in different speed-ups for the same problem

Workflow with PIPS-IPM



Running REMix with PIPS-IPM I

ID	Instance	Variation	Regions	PIPS Version	MPI threads	Last iteration	Runtime (sec.)	State
1149052	YSSP	disp	30	PIPS_gps_2018b_8apr	60	55	323	SUCCESSFUL TERMINATION
1149053	YSSP	disp	30	PIPS_gps_2018b_8apr	120	53	251.02	SUCCESSFUL TERMINATION
1149054	YSSP	disp	30	PIPS_gps_2018b_8apr	292	8	92.88	SEGMENTATION FAULT
1149056	YSSP	exp	30	PIPS_gps_2018b_8apr	60	130	1236.58	SUCCESSFUL TERMINATION
1149057	YSSP	exp	30	PIPS_gps_2018b_8apr	120	133	963.19	SUCCESSFUL TERMINATION
1149058	YSSP	exp	30	PIPS_gps_2018b_8apr	292	12	226.18	SEGMENTATION FAULT
1149060	YSSP	disp	120	PIPS_gps_2018b_8apr	60	68	1153.34	SUCCESSFUL TERMINATION
1149061	YSSP	disp	120	PIPS_gps_2018b_8apr	120	67	825.51	SUCCESSFUL TERMINATION
1149062	YSSP	disp	120	PIPS_gps_2018b_8apr	292	71	861.66	SEGMENTATION FAULT
1149064	YSSP	exp	120	PIPS_gps_2018b_8apr	60	19	1131.85	SEGMENTATION FAULT
1149065	YSSP	exp	120	PIPS_gps_2018b_8apr	120	10	28812.43	CANCELLED DUE TO TIME LIMIT
1149066	YSSP	exp	120	PIPS_gps_2018b_8apr	292	-	14.4	MPI ERROR
1149068	YSSP	disp	488	PIPS_gps_2018b_8apr	60	26	1930.75	SEGMENTATION FAULT
1149069	YSSP	disp	488	PIPS_gps_2018b_8apr	120	14	21578.14	CANCELLED DUE TO TIME LIMIT
1149070	YSSP	disp	488	PIPS_gps_2018b_8apr	292	-	45.81	-
1149072	YSSP	exp	488	PIPS_gps_2018b_8apr	60	-	-	-
1149073	YSSP	exp	488	PIPS_gps_2018b_8apr	120	-	559.61	-
1149074	YSSP	exp	488	PIPS_gps_2018b_8apr	292	-	37.44	-

PIPS-IPM does not run ‘out-of-the-box’ and is still in development

Running REMix with PIPS-IPM II

ID	Instance	Variation	Regions	PIPS Version	MPI threads	Last iteration	Runtime (sec.)	State
1267	YSSP	disp	30	linking-zib-pardiso	16	54	868.27	SUCCESSFUL TERMINATION
1268	YSSP	disp	30	linking-zib-pardiso	24	53	718.54	SUCCESSFUL TERMINATION
1269	YSSP	disp	30	linking-zib-pardiso	32	54	701.98	SUCCESSFUL TERMINATION
1270	YSSP	disp	30	linking-zib-pardiso	48	54	677.32	SUCCESSFUL TERMINATION
1271	YSSP	disp	30	linking-zib-pardiso	64	54	675.63	SUCCESSFUL TERMINATION

Commercial solver @ DLR ENT-U

512 GB RAM

16 cores

Barrier tolerance 1e-5

Runtime: **392 sec.**

PIPS-IPM @ DLR ENT-U

8 x 128 GB RAM

8 x 24 cores

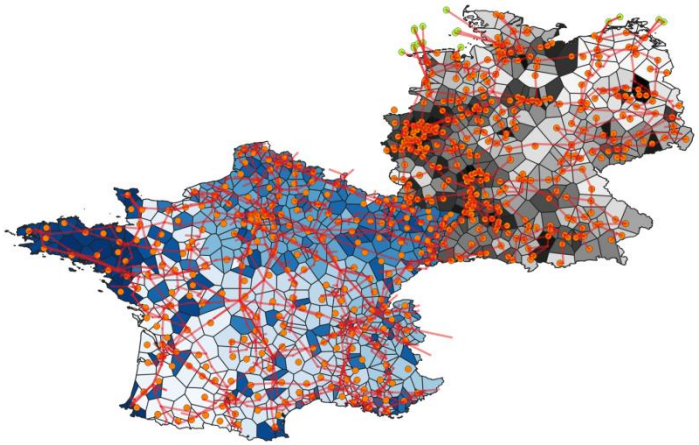
(64 MPI threads on 8 nodes)

Barrier tolerance 1e-5

Runtime: **675 sec.**

No performance gain for small instances despite more hardware utilization

Running REMix with PIPS-IPM III



problem size
488 regions

87.2 mio. variables
73.4 mio. equations
264.9 mio non-zeros
+ optimization of grid and storage capacities

Commercial solver @ ENT-U

512 GB RAM

16 cores

Barrier tolerance 1e-5

Runtime: **155 472 sec.**

PIPS-IPM @ JSC JUWELS

10 x 96 GB RAM

10 x 48 cores

(120 MPI threads on 10 nodes)

Barrier tolerance 1e-5

Runtime: **5 838 sec.**

PIPS-IPM can outperform commercial solvers in real-world REMix instances

Key takeaways

PIPS-IPM is a significant first step towards general ESM on HPC

Good annotation requires detailed domain knowledge

Number of blocks corresponds to the parallelism which can be achieved

PIPS-IPM can outperform commercial solvers in large scale REMix instances

Project BEAM-ME

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