Multiple Objectives for Residential PV

Set up.

One only needs to execute the following line once, in order to make sure recent enough packages are installed.

In [1]:
```
#!pip install 'numpy>=1.17.2' 'pandas>=0.25.1'
```

Import packages.

In [2]:
```
import os
import sys
sys.path.insert(0, os.path.abspath("../src"))
```

In [3]:
```
import numpy             as np
import matplotlib.pyplot as pl
import pandas            as pd
import re                as re
import scipy.stats       as st
import seaborn           as sb

# The `tyche` package is located at <https://github.com/NREL/portfolio/tree/master/production-function/framework/src/tyche/>.
import tyche             as ty

from copy import deepcopy
```

Load data.

The data are stored in a set of tab-separated value files in a folder.

In [4]:
```
designs = ty.Designs("../data/residential_pv_multiobjective")
```

In [5]:
```
investments = ty.Investments("../data/residential_pv_multiobjective")
```

Compile the production and metric functions for each technology in the dataset.

```
In [6]: designs.compile()
```

Examine the data.

The `functions` table specifies where the Python code for each technology resides.

```
In [7]: designs.functions
```

Out[7]:

Technology	Style	Module	Capital	Fixed	Production	Metrics	Notes
Residential PV	numpy	residential_pv_multiobjective	capital_cost	fixed_cost	production	metrics	

Right now, only the style `numpy` is supported.

The `indices` table defines the subscripts for variables.

```
In [8]: designs.indices
```

Out[8]:

Technology	Type	Index	Offset	Description	Notes
Residential PV	Capital	BoS	2	balance of system	
		Inverter	1	system inverters	
		Module	0	system module	
	Fixed	System	0	whole system	
	Input	NaN	0	no inputs	
	Metric	GHG	2	reduction in GHGs	
		LCOE	0	reduction in levelized cost of energy	
		Labor	1	increase in spending on wages	
	Output	Electricity	0	electricity generated	

The `designs` table contains the cost, input, efficiency, and price data for a scenario.

In [9]:
```
designs.designs
```

Out[9]:

				Value	Units	Notes
Technology	**Scenario**	**Variable**	**Index**			
Residential PV	2015 Actual	Input	NaN	0	1	no inputs
		Input efficiency	NaN	1	1	no inputs
		Input price	NaN	0	1	no inputs
		Lifetime	BoS	1	system-lifetime	per-lifetime computations
			Inverter	1	system-lifetime	per-lifetime computations
	...	...	...	...	...	...
	Module Slow Progress	Lifetime	Inverter	1	system-lifetime	per-lifetime computations
			Module	1	system-lifetime	per-lifetime computations
		Output efficiency	Electricity	1	W/W	see parameter table for individual efficiencies
		Output price	Electricity	0	$/kWh	not tracking electricity price
		Scale	NaN	1	system/system	no scaling

90 rows × 3 columns

The `parameters` table contains additional techno-economic parameters for each technology.

```
In [10]: designs.parameters
```

Out[10]:

Technology	Scenario	Parameter	Offset	Value	Units	Notes
Residential PV	2015 Actual	Customer Acquisition	19	st.triang(0.5, loc=2000, scale=0.2)	$/system	BCA
		DC-to-AC Ratio	15	st.triang(0.5, loc=1.4, scale=0.00014)	1	IDC
		Direct Labor	17	st.triang(0.5, loc=2000, scale=0.2)	$/system	BLR
		Discount Rate	0	0.07	1/year	DR
		Hardware Capital	16	st.triang(0.5, loc=80, scale=0.008)	$/m^2	BCC
	...	...	...	...	...	...
	Module Slow Progress	Module Lifetime	4	st.triang(0.5, loc=26, scale=1)	yr	MLT
		Module O&M Fixed	7	st.triang(0.5, loc=19, scale=0.5)	$/kWyr	MOM
		Module Soiling Loss	10	st.triang(0.5, loc=0.05, scale=10E-06)	1	MSL
		Permitting	18	st.triang(0.5, loc=600, scale=0.06)	$/system	BPR
		System Size	2	36	m^2	SSZ

210 rows × 4 columns

The `results` table specifies the units of measure for results of computations.

```
In [11]: designs.results
```

Out[11]:

Technology	Variable	Index	Units	Notes
Residential PV	Cost	Cost	$/system	
	Metric	GHG	ΔgCO2e/system	
		LCOE	Δ$/kWh	
		Labor	Δ$/system	
	Output	Electricity	kWh	

The `tranches` table specifies multually exclusive possibilities for investments: only one `Tranch` may be selected for each `Category`.

In [12]:
```
investments.tranches
```

Out[12]:

Category	Tranche	Scenario	Amount	Notes
BoS R&D	BoS High R&D	Bos Fast Progress	900000.0	
	BoS Low R&D	BoS Slow Progress	300000.0	
	BoS Medium R&D	Bos Moderate Progress	600000.0	
Inverter R&D	Inverter High R&D	Inverter Fast Progress	3000000.0	
	Inverter Low R&D	Inverter Slow Progress	1000000.0	
	Inverter Medium R&D	Inverter Moderate Progress	2000000.0	
Module R&D	Module High R&D	Module Fast Progress	4500000.0	
	Module Low R&D	Module Slow Progress	1500000.0	
	Module Medium R&D	Module Moderate Progress	3000000.0	

The `investments` table bundles a consistent set of tranches (one per category) into an overall investment.

In [13]:
```
investments.investments
```

Out[13]:

Investment	Category	Tranche	Notes
High R&D	BoS R&D	BoS High R&D	
	Inverter R&D	Inverter High R&D	
	Module R&D	Module High R&D	
Low R&D	BoS R&D	BoS Low R&D	
	Inverter R&D	Inverter Low R&D	
	Module R&D	Module Low R&D	
Medium R&D	BoS R&D	BoS Medium R&D	
	Inverter R&D	Inverter Medium R&D	
	Module R&D	Module Medium R&D	

Evaluate the scenarios in the dataset.

In [14]:
```
scenario_results = designs.evaluate_scenarios(sample_count=50)
```

In [15]:
```
scenario_results.xs(1, level="Sample", drop_level=False)
```

Out[15]:

Technology	Scenario	Sample	Variable	Index	Value	Units
Residential PV			Cost	Cost	19539.227944	$/system
				GHG	-0.004906	ΔgCO2e/system
	2015 Actual	1	Metric	LCOE	-0.000009	Δ$/kWh
				Labor	-0.009447	Δ$/system
			Output	Electricity	184100.029294	kWh
			Cost	Cost	17560.275391	$/system
				GHG	-0.002930	ΔgCO2e/system
	BoS Fast Progress	1	Metric	LCOE	0.010743	Δ$/kWh
				Labor	-484.964445	Δ$/system
			Output	Electricity	184104.428731	kWh
			Cost	Cost	17930.790363	$/system
				GHG	-0.008140	ΔgCO2e/system
	BoS Moderate Progress	1	Metric	LCOE	0.008724	Δ$/kWh
				Labor	-355.032086	Δ$/system
			Output	Electricity	184092.828163	kWh
			Cost	Cost	19001.261275	$/system
				GHG	0.000722	ΔgCO2e/system
	BoS Slow Progress	1	Metric	LCOE	0.002920	Δ$/kWh
				Labor	-170.988190	Δ$/system
			Output	Electricity	184112.562550	kWh
			Cost	Cost	17927.843781	$/system
				GHG	2.073089	ΔgCO2e/system
	Inverter Fast Progress	1	Metric	LCOE	0.011132	Δ$/kWh
				Labor	0.014390	Δ$/system
			Output	Electricity	188727.498356	kWh
			Cost	Cost	18549.854277	$/system
				GHG	2.454672	ΔgCO2e/system
	Inverter Moderate Progress	1	Metric	LCOE	0.008276	Δ$/kWh
				Labor	-0.016391	Δ$/system
			Output	Electricity	189577.242742	kWh
	Inverter Slow Progress	1	Cost	Cost	19283.451011	$/system
				GHG	2.402211	ΔgCO2e/system
			Metric	LCOE	0.004344	Δ$/kWh
				Labor	0.028991	Δ$/system

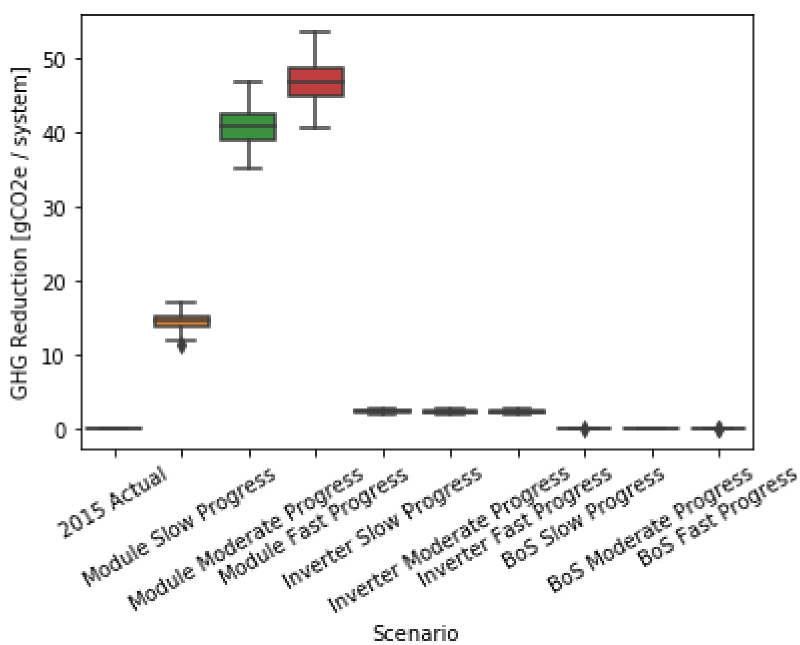
					Value	Units
Technology	Scenario	Sample	Variable	Index		
			Output	Electricity	189460.418312	kWh
			Cost	Cost	18836.689674	$/system
				GHG	50.035249	ΔgCO2e/system
	Module Fast Progress	1	Metric	LCOE	0.042387	Δ$/kWh
				Labor	-0.024688	Δ$/system
			Output	Electricity	295534.037838	kWh
			Cost	Cost	18959.524231	$/system
				GHG	43.536179	ΔgCO2e/system
	Module Moderate Progress	1	Metric	LCOE	0.038668	Δ$/kWh
				Labor	0.054460	Δ$/system
			Output	Electricity	281061.312296	kWh
			Cost	Cost	19568.582984	$/system
				GHG	13.834233	ΔgCO2e/system
	Module Slow Progress	1	Metric	LCOE	0.015074	Δ$/kWh
				Labor	-0.024580	Δ$/system
			Output	Electricity	214918.292681	kWh

Save results.

In [16]:
```
scenario_results.to_csv("output/residential_pv_multiobjective/example-scenario.csv")
```

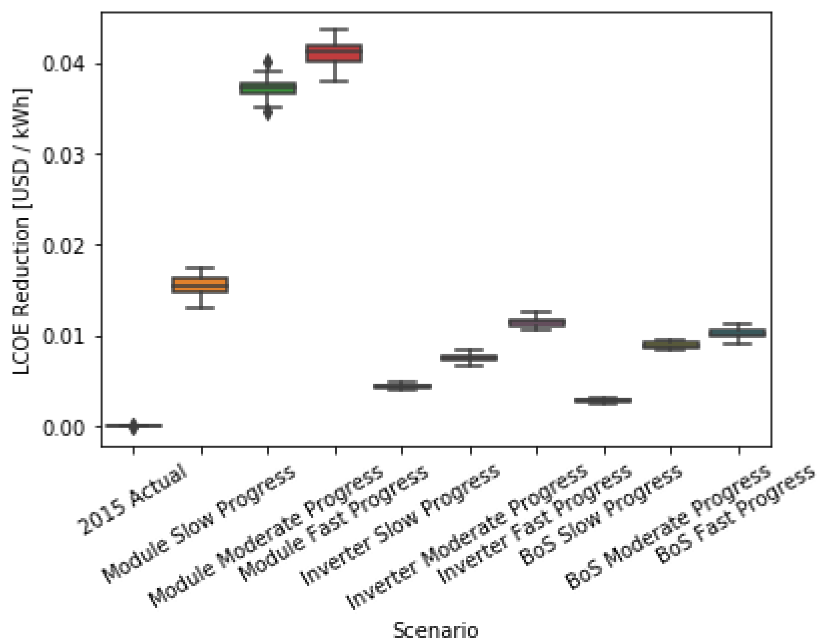
Plot GHG metric.

```
In [17]: g = sb.boxplot(
             x="Scenario",
             y="Value",
             data=scenario_results.xs(
                 ["Metric", "GHG"],
                 level=["Variable", "Index"]
             ).reset_index()[["Scenario", "Value"]],
             order=[
                 "2015 Actual"                ,
                 "Module Slow Progress"        ,
                 "Module Moderate Progress"    ,
                 "Module Fast Progress"        ,
                 "Inverter Slow Progress"      ,
                 "Inverter Moderate Progress",
                 "Inverter Fast Progress"      ,
                 "BoS Slow Progress"           ,
                 "BoS Moderate Progress"       ,
                 "BoS Fast Progress"           ,
             ]
         )
         g.set(ylabel="GHG Reduction [gCO2e / system]")
         g.set_xticklabels(g.get_xticklabels(), rotation=30);
```



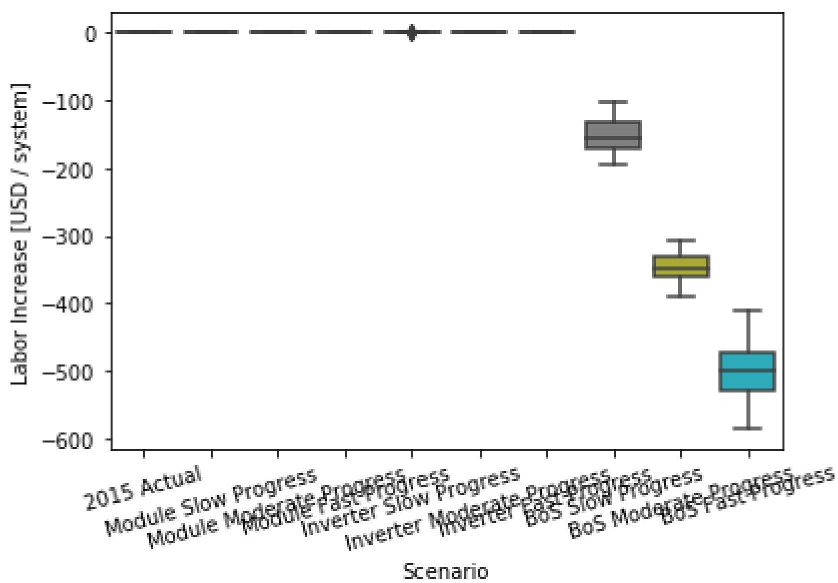
Plot LCOE metric.

In [18]:
```
g = sb.boxplot(
    x="Scenario",
    y="Value",
    data=scenario_results.xs(
        ["Metric", "LCOE"],
        level=["Variable", "Index"]
    ).reset_index()[["Scenario", "Value"]],
    order=[
        "2015 Actual"                 ,
        "Module Slow Progress"         ,
        "Module Moderate Progress"     ,
        "Module Fast Progress"         ,
        "Inverter Slow Progress"       ,
        "Inverter Moderate Progress",
        "Inverter Fast Progress"       ,
        "BoS Slow Progress"            ,
        "BoS Moderate Progress"        ,
        "BoS Fast Progress"            ,
    ]
)
g.set(ylabel="LCOE Reduction [USD / kWh]")
g.set_xticklabels(g.get_xticklabels(), rotation=30);
```



Plot labor metric.

In [19]:
```
g = sb.boxplot(
    x="Scenario",
    y="Value",
    data=scenario_results.xs(
        ["Metric", "Labor"],
        level=["Variable", "Index"]
    ).reset_index()[["Scenario", "Value"]],
    order=[
        "2015 Actual"                  ,
        "Module Slow Progress"         ,
        "Module Moderate Progress"     ,
        "Module Fast Progress"         ,
        "Inverter Slow Progress"       ,
        "Inverter Moderate Progress",
        "Inverter Fast Progress"       ,
        "BoS Slow Progress"            ,
        "BoS Moderate Progress"        ,
        "BoS Fast Progress"            ,
    ]
)
g.set(ylabel="Labor Increase [USD / system]")
g.set_xticklabels(g.get_xticklabels(), rotation=15);
```



Evaluate the investments in the dataset.

In [20]:
```
investment_results = investments.evaluate_investments(designs, sample_co
unt=50)
```

Costs of investments.

```
In [21]: investment_results.amounts
```

Out[21]:

Investment	Amount
High R&D	8400000.0
Low R&D	2800000.0
Medium R&D	5600000.0

Benefits of investments.

```
In [22]: investment_results.metrics.xs(1, level="Sample", drop_level=False)
```

Out[22]:

Investment	Category	Tranche	Scenario	Sample	Technology	Index	Value	Unit
Low R&D	BoS R&D	BoS Low R&D	BoS Slow Progress	1	Residential PV	GHG	-0.003736	ΔgCO2e/syste
						LCOE	0.002792	Δ$/kW
						Labor	-154.121648	Δ$/syste
High R&D	Inverter R&D	Inverter High R&D	Inverter Fast Progress	1	Residential PV	GHG	2.222498	ΔgCO2e/syste
						LCOE	0.011431	Δ$/kW
						Labor	-0.036005	Δ$/syste
Medium R&D	Inverter R&D	Inverter Medium R&D	Inverter Moderate Progress	1	Residential PV	GHG	2.529230	ΔgCO2e/syste
						LCOE	0.007250	Δ$/kW
						Labor	0.059053	Δ$/syste
Low R&D	Inverter R&D	Inverter Low R&D	Inverter Slow Progress	1	Residential PV	GHG	2.311315	ΔgCO2e/syste
						LCOE	0.004397	Δ$/kW
						Labor	-0.015249	Δ$/syste
High R&D	Module R&D	Module High R&D	Module Fast Progress	1	Residential PV	GHG	51.608236	ΔgCO2e/syste
						LCOE	0.043701	Δ$/kW
						Labor	0.079159	Δ$/syste
Medium R&D	Module R&D	Module Medium R&D	Module Moderate Progress	1	Residential PV	GHG	38.543220	ΔgCO2e/syste
						LCOE	0.035966	Δ$/kW
						Labor	-0.030530	Δ$/syste
Low R&D	Module R&D	Module Low R&D	Module Slow Progress	1	Residential PV	GHG	16.062350	ΔgCO2e/syste
						LCOE	0.016943	Δ$/kW
						Labor	-0.022079	Δ$/syste

In [23]:
```
investment_results.summary.xs(1, level="Sample", drop_level=False)
```

Out[23]:

Investment	Sample	Index	Value	Units
Low R&D	1.0	GHG	18.369929	ΔgCO2e/system
		LCOE	0.024131	Δ$/kWh
		Labor	-154.158977	Δ$/system
High R&D	1.0	GHG	53.830735	ΔgCO2e/system
		LCOE	0.055133	Δ$/kWh
		Labor	0.043155	Δ$/system
Medium R&D	1.0	GHG	41.072450	ΔgCO2e/system
		LCOE	0.043216	Δ$/kWh
		Labor	0.028523	Δ$/system

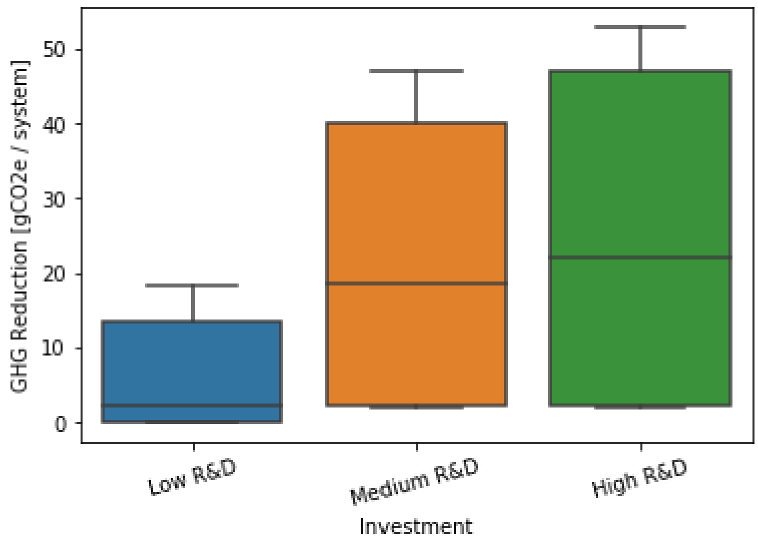
Save results.

In [24]:
```
investment_results.amounts.to_csv("output/residential_pv_multiobjective/
example-investment-amounts.csv")
```

In [25]:
```
investment_results.metrics.to_csv("output/residential_pv_multiobjective/
example-investment-metrics.csv")
```

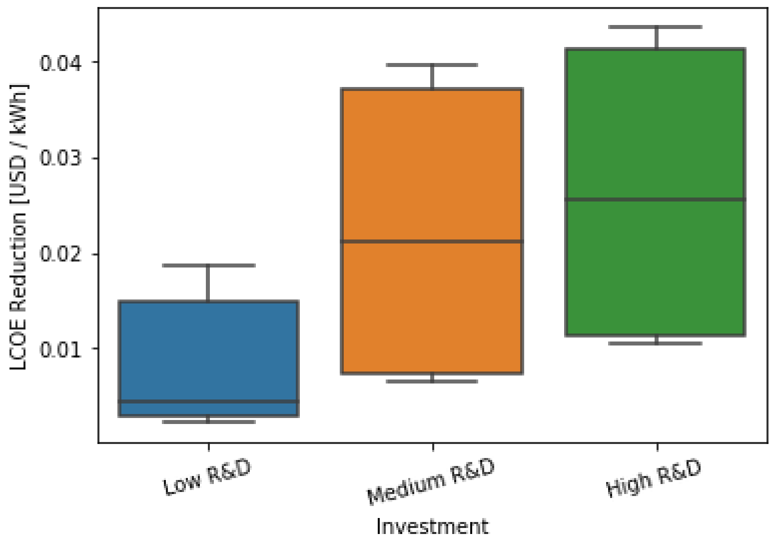
Plot GHG metric.

In [26]:
```
g = sb.boxplot(
    x="Investment",
    y="Value",
    data=investment_results.metrics.xs(
        "GHG",
        level="Index"
    ).reset_index()[["Investment", "Value"]],
    order=[
        "Low R&D"    ,
        "Medium R&D",
        "High R&D"   ,
    ]
)
g.set(ylabel="GHG Reduction [gCO2e / system]")
g.set_xticklabels(g.get_xticklabels(), rotation=15);
```



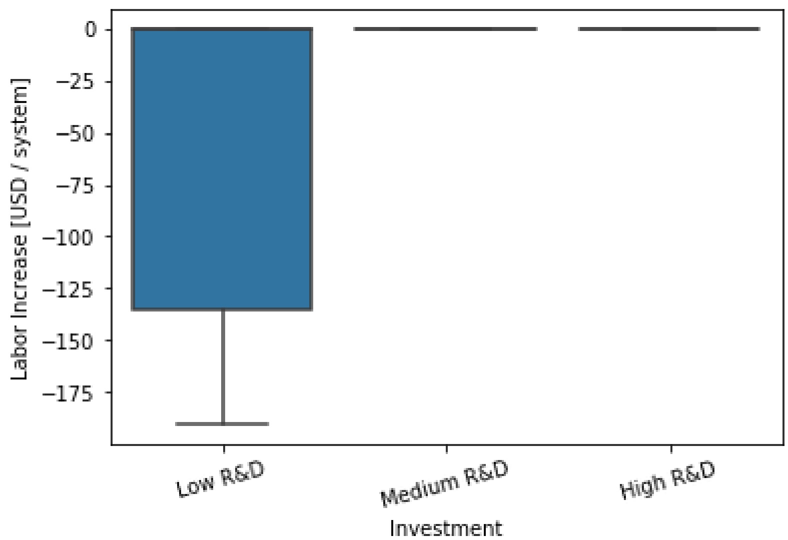
Plot LCOE metric.

In [27]:
```
g = sb.boxplot(
    x="Investment",
    y="Value",
    data=investment_results.metrics.xs(
        "LCOE",
        level="Index"
    ).reset_index()[["Investment", "Value"]],
    order=[
        "Low R&D"    ,
        "Medium R&D",
        "High R&D"   ,
    ]
)
g.set(ylabel="LCOE Reduction [USD / kWh]")
g.set_xticklabels(g.get_xticklabels(), rotation=15);
```



Plot labor metric.

In [28]:
```
g = sb.boxplot(
    x="Investment",
    y="Value",
    data=investment_results.metrics.xs(
        "Labor",
        level="Index"
    ).reset_index()[["Investment", "Value"]],
    order=[
        "Low R&D"   ,
        "Medium R&D",
        "High R&D"  ,
    ]
)
g.set(ylabel="Labor Increase [USD / system]")
g.set_xticklabels(g.get_xticklabels(), rotation=15);
```



Multi-objective decision analysis.

THIS IS A WORK IN PROGRESS.

Compute costs and metrics for tranches.

Tranches are atomic units for building investment portfolios. Evaluate all of the tranches, so we can assemble them into investments (portfolios).

In [29]:
```
tranche_results = investments.evaluate_tranches(designs, sample_count=500)
```

Display the cost of each tranche.

In [30]:
```
tranche_results.amounts
```
Out[30]:

Category	Tranche	Amount
BoS R&D	BoS High R&D	900000.0
	BoS Low R&D	300000.0
	BoS Medium R&D	600000.0
Inverter R&D	Inverter High R&D	3000000.0
	Inverter Low R&D	1000000.0
	Inverter Medium R&D	2000000.0
Module R&D	Module High R&D	4500000.0
	Module Low R&D	1500000.0
	Module Medium R&D	3000000.0

Display the metrics for each tranche.

In [31]:
```
tranche_results.summary
```
Out[31]:

Category	Tranche	Sample	Index	Value	Units
BoS R&D	BoS Low R&D	1.0	GHG	-0.008180	ΔgCO2e/system
			LCOE	0.002697	Δ$/kWh
			Labor	-141.625878	Δ$/system
		2.0	GHG	0.001385	ΔgCO2e/system
			LCOE	0.002853	Δ$/kWh
...	...	...	...	...	...
Module R&D	Module Low R&D	499.0	LCOE	0.015400	Δ$/kWh
			Labor	-0.013703	Δ$/system
		500.0	GHG	15.055054	ΔgCO2e/system
			LCOE	0.016352	Δ$/kWh
			Labor	-0.039216	Δ$/system

10500 rows × 2 columns

Save the results.

In [32]:

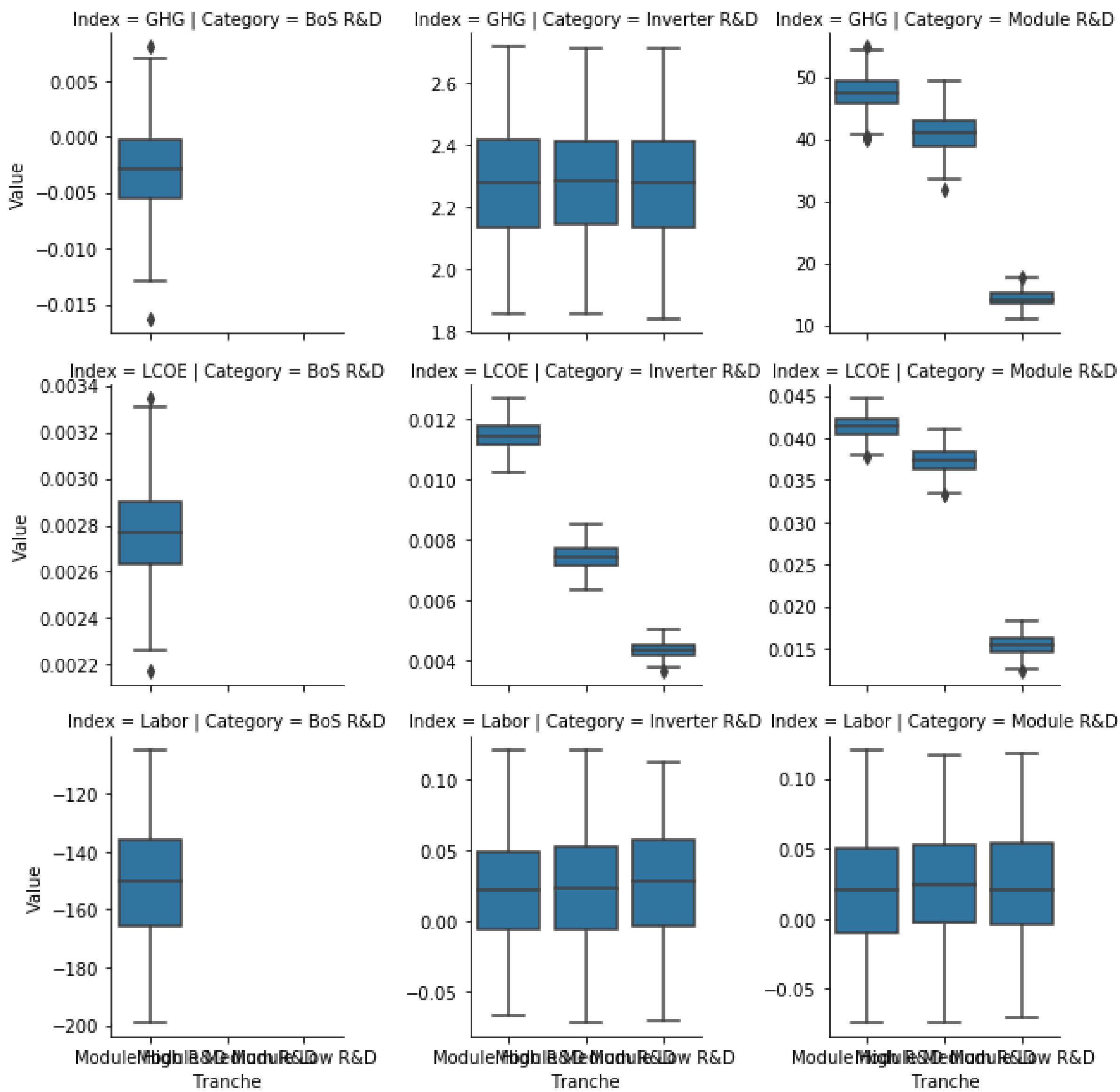
```
tranche_results.amounts.to_csv("output/residential_pv_multiobjective/example-tranche-amounts.csv")
tranche_results.summary.to_csv("output/residential_pv_multiobjective/example-tranche-summary.csv")
```

Here is an incomplete work-in-progress on plotting metrics for tranches. The axis labels etc. need fixing.

In [33]:
```
g = sb.FacetGrid(
    tranche_results.summary.reset_index(),#.set_index(["Category", "Tran
che"]).join(tranche_results.amount).reset_index(),
    row="Index",
    col="Category",
#    row_order=["LCOE", "GHG", "Labor"],
#    col_order=["Module R&D", "Inverter R&D", "BoS R&D"],
    sharex=True,
    sharey=False,
)
g.map(sb.boxplot, "Tranche", "Value")
```

```
/nix/store/f9jr3lh0ix952h7lr0xiwq9gkl1yckk1-python3-3.6.9-env/lib/pytho
n3.6/site-packages/seaborn/axisgrid.py:715: UserWarning: Using the boxp
lot function without specifying `order` is likely to produce an incorre
ct plot.
  warnings.warn(warning)
```

Out[33]: <seaborn.axisgrid.FacetGrid at 0x7fca48641be0>



Compute all combinations of tranches.

Set up investment scenarios.

We're just building all legal combinations of tranches into investment portfolios.

In [34]:
```
z = None
for imod in np.append(investments.tranches.xs("Module R&D").reset_index(
"Scenario").index.unique().values, ""):
    for iinv in np.append(investments.tranches.xs("Inverter R&D").reset_
index("Scenario").index.unique().values, ""):
        for ibos in np.append(investments.tranches.xs("BoS R&D").reset_i
ndex("Scenario").index.unique().values, ""):
            w = None
            name = imod
            if iinv != "":
                if name != "":
                    name = name + " + "
                name = name + iinv
            if ibos != "":
                if name != "":
                    name = name + " + "
                name = name + ibos
            if imod != "":
                w = pd.DataFrame({
                    "Investment" : [name        ],
                    "Category"   : ["Module R&D"],
                    "Tranche"    : [imod        ],
                    "Notes"      : [""          ],
                }).append(w)
            if iinv != "":
                w = pd.DataFrame({
                    "Investment" : [name          ],
                    "Category"   : ["Inverter R&D"],
                    "Tranche"    : [iinv          ],
                    "Notes"      : [""            ],
                }).append(w)
            if ibos != "":
                w = pd.DataFrame({
                    "Investment" : [name     ],
                    "Category"   : ["BoS R&D"],
                    "Tranche"    : [ibos     ],
                    "Notes"      : [""       ],
                }).append(w)
            if w is not None:
                z = w.append(z)
z.set_index(["Investment", "Category", "Tranche"], inplace=True)
investments.investments = z
z
```

Out[34]:

Investment	Category	Tranche	Notes
BoS Medium R&D	BoS R&D	BoS Medium R&D	
BoS Low R&D	BoS R&D	BoS Low R&D	
BoS High R&D	BoS R&D	BoS High R&D	
Inverter Medium R&D	Inverter R&D	Inverter Medium R&D	
Inverter Medium R&D + BoS Medium R&D	BoS R&D	BoS Medium R&D	
...	...	...	...
Module High R&D + Inverter High R&D + BoS Low R&D	Inverter R&D	Inverter High R&D	
	Module R&D	Module High R&D	
Module High R&D + Inverter High R&D + BoS High R&D	BoS R&D	BoS High R&D	
	Inverter R&D	Inverter High R&D	
	Module R&D	Module High R&D	

144 rows × 1 columns

Evaluate the investments.

In [35]:
```
investment_results = investments.evaluate_investments(designs, sample_co
unt=50)
```

In [36]:
```
investment_results.amounts
```

Out[36]:

Investment	Amount
BoS High R&D	900000.0
Inverter Medium R&D + BoS High R&D	2900000.0
Inverter Low R&D + BoS High R&D	1900000.0
Inverter High R&D + BoS High R&D	3900000.0
Module Medium R&D + BoS High R&D	3900000.0
...	...
Module Low R&D + Inverter Medium R&D	3500000.0
Module High R&D + Inverter Medium R&D	6500000.0
Module High R&D	4500000.0
Module Low R&D	1500000.0
Module Medium R&D	3000000.0

63 rows × 1 columns

In [37]:
```
investment_results.summary.xs(1, level="Sample", drop_level=False)
```

Out[37]:

			Value	Units
Investment	**Sample**	**Index**		
BoS Low R&D	1.0	GHG	0.000405	ΔgCO2e/system
		LCOE	0.002630	Δ$/kWh
		Labor	-139.177759	Δ$/system
Inverter Medium R&D + BoS Low R&D	1.0	GHG	1.918760	ΔgCO2e/system
		LCOE	0.009344	Δ$/kWh
...	...	...	...	...
Module Low R&D + BoS Medium R&D	1.0	LCOE	0.015399	Δ$/kWh
		Labor	0.023847	Δ$/system
Module Low R&D + BoS High R&D	1.0	GHG	14.708698	ΔgCO2e/system
		LCOE	0.015399	Δ$/kWh
		Labor	0.023847	Δ$/system

183 rows × 2 columns

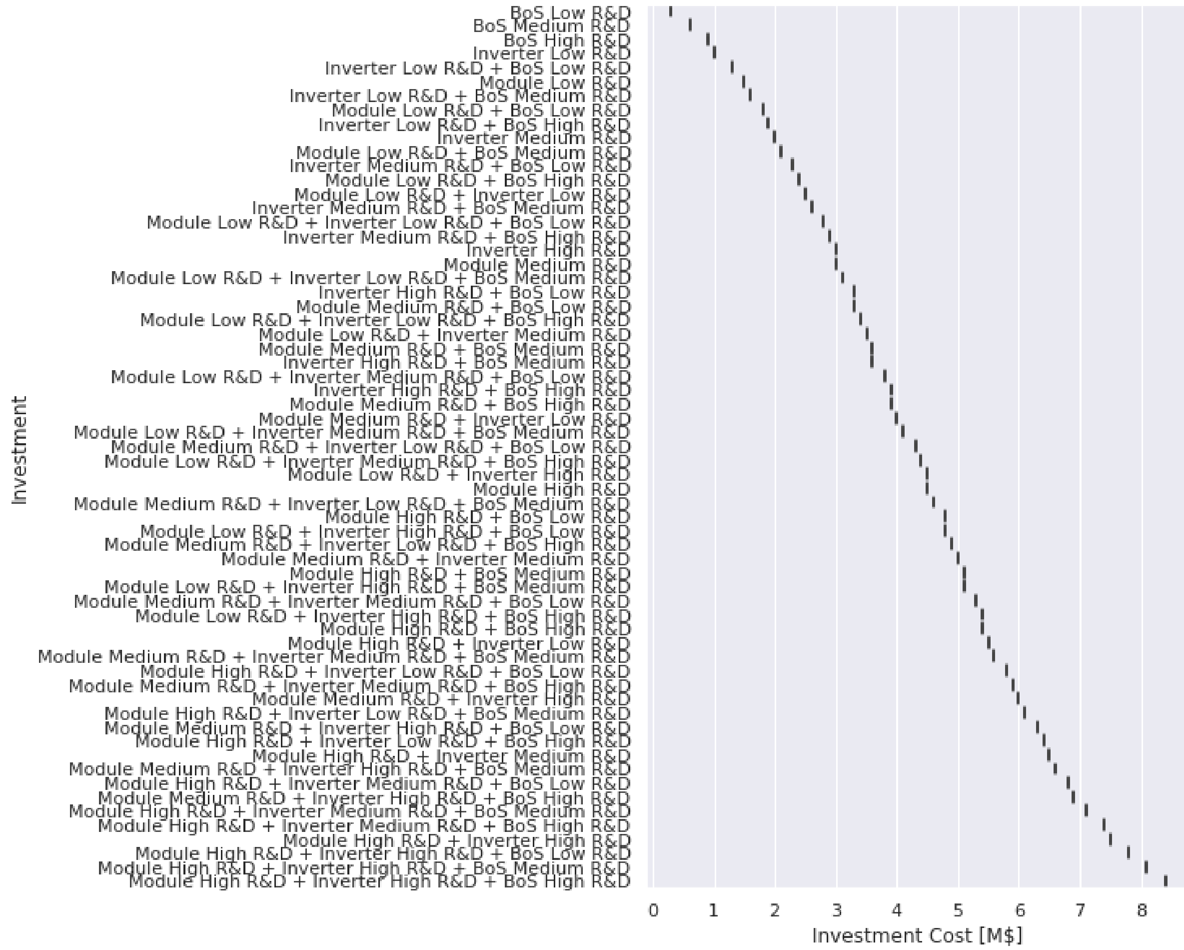
Plot the results.

In [38]:
```
w = investment_results.summary.reset_index(
).set_index(
    ["Investment"]
).join(
    investment_results.amounts
).reset_index(
).set_index(
    ["Index"]
)
ww = investment_results.amounts.reset_index().sort_values("Amount")["Inv
estment"]
```

In [39]:
```
sb.set(rc={'figure.figsize':(6, 10)})
```

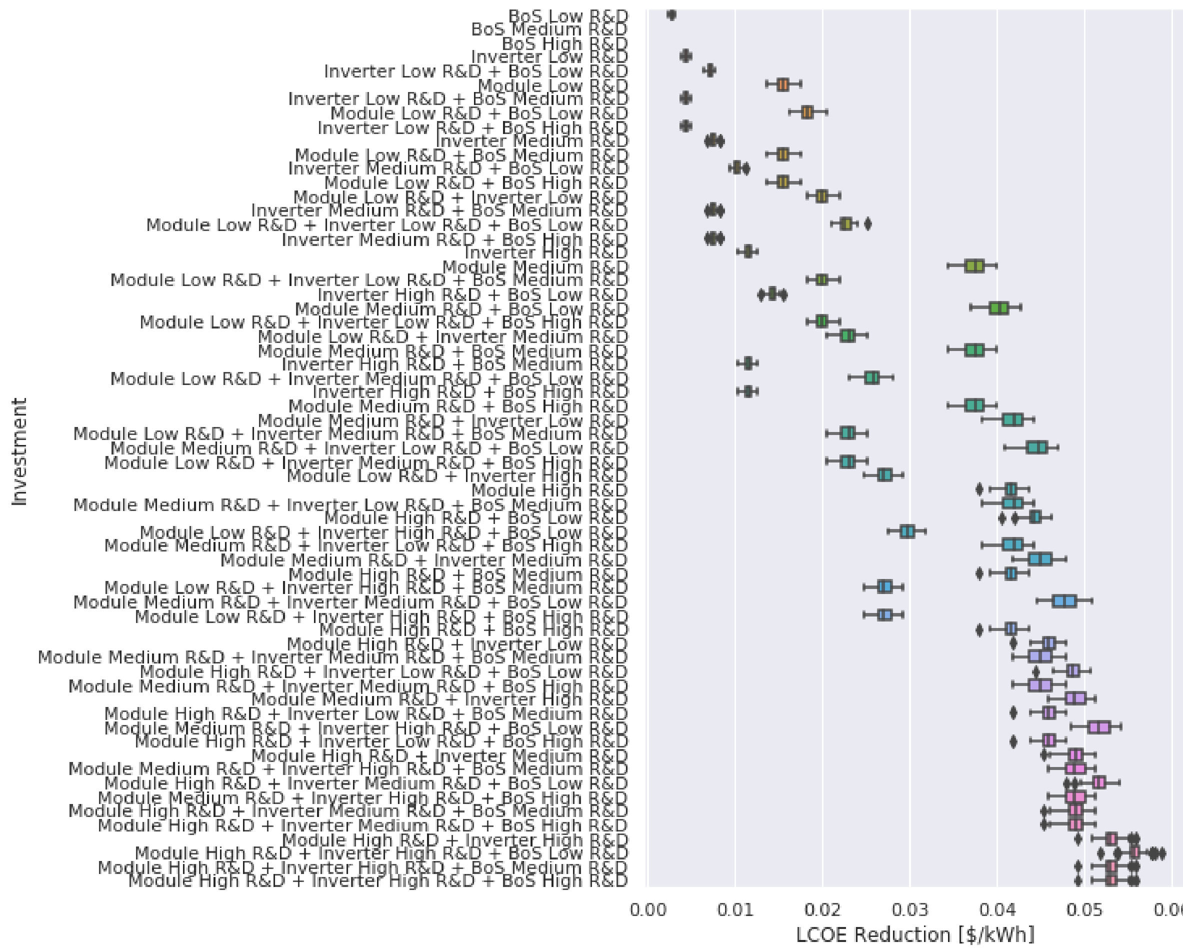
Cost of investments.

```
In [40]: www = investment_results.amounts.reset_index()
         www["Amount"] = www["Amount"] / 1e6
         g = sb.boxplot(data=www, y="Investment", x="Amount", orient="h", order=w
         w)
         g.set(xlabel="Investment Cost [M$]");
         #pl.savefig('example-amounts.png')
```



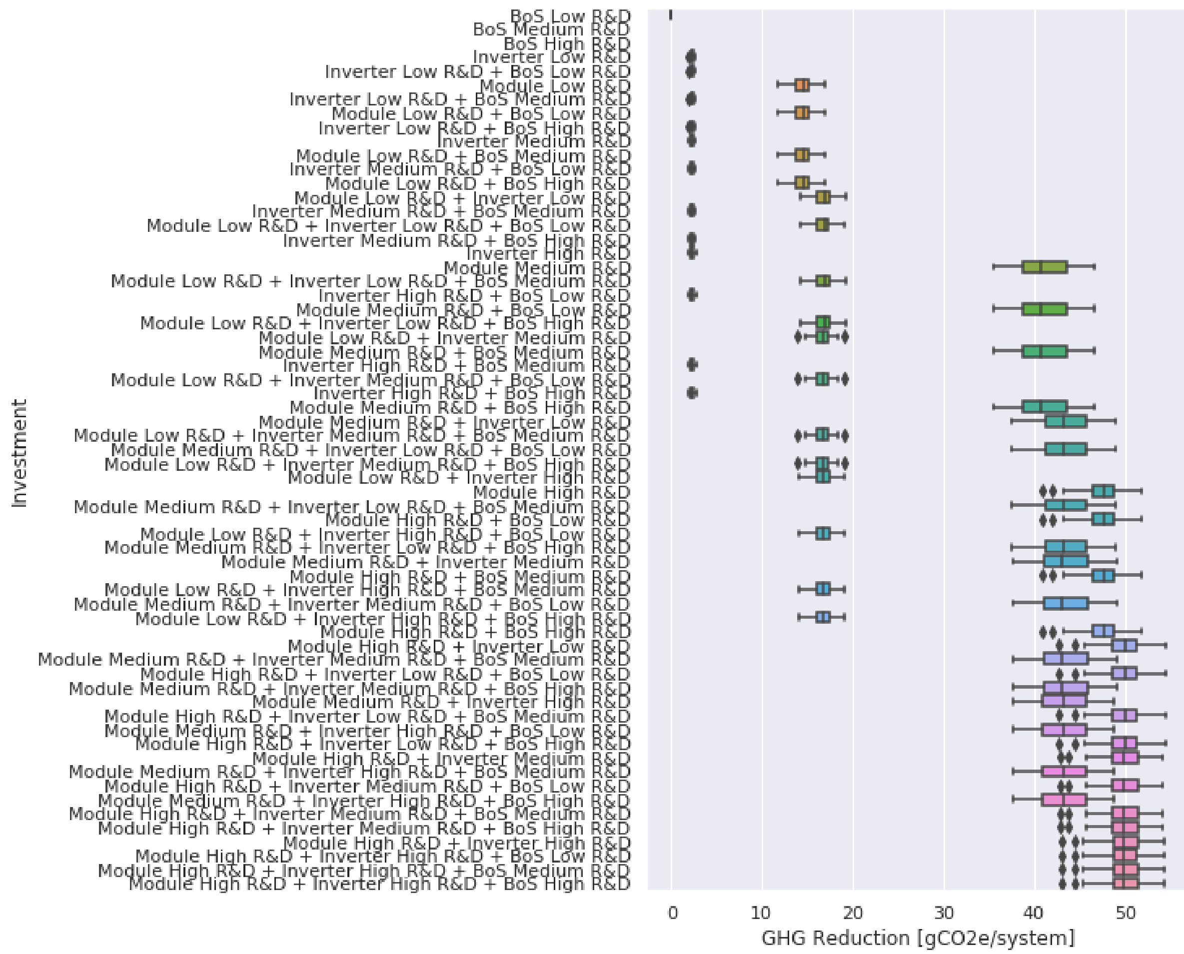
LOCE benefits.

In [41]:
```
g = sb.boxplot(data=w.xs("LCOE"), y="Investment", x="Value", orient="h",
order=ww)
g.set(xlabel="LCOE Reduction [$/kWh]");
```



GHG benefits.

```
In [42]: g = sb.boxplot(data=w.xs("GHG"), y="Investment", x="Value", orient="h",
         order=ww)
         g.set(xlabel="GHG Reduction [gCO2e/system]");
```



Labor benefits.

In [43]:
```
g = sb.boxplot(data=w.xs("Labor"), y="Investment", x="Value", orient="h"
, order=ww)
g.set(xlabel="Labor Increase [$/system]");
```